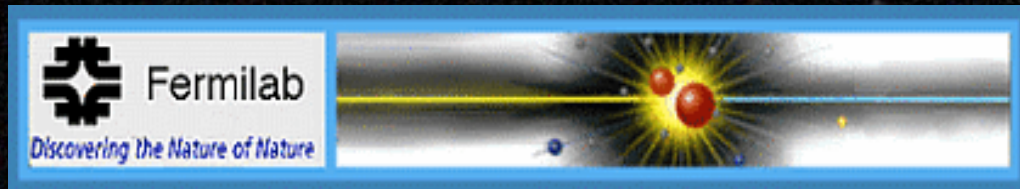


# Mapping the Heavens: The Universe Revealed by the Sloan Digital Sky Survey

Josh Frieman





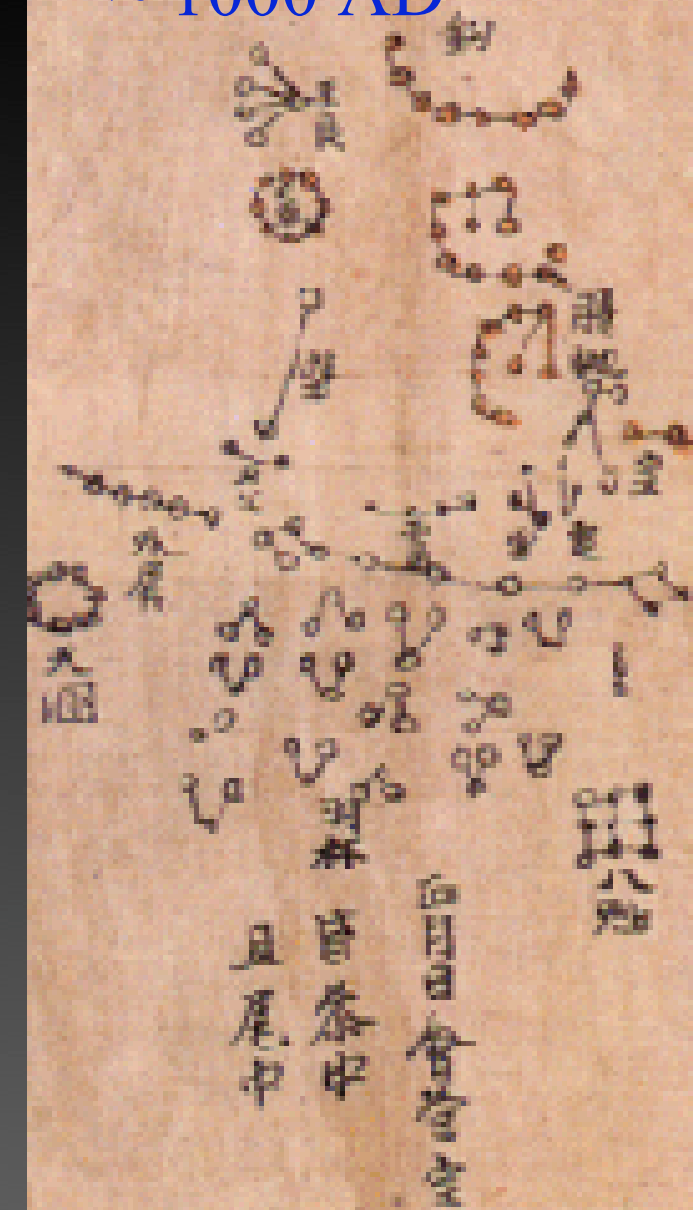


# Chinese star chart ~ 1000 AD

古已上合氣象有八極之旨方有極限之也亦謂焉者不  
 祇指入此界不極宜宜是故情極而歸之具如前傳  
 陳隋庭臣加氣經此罪死罪謫言



自世八度至危十五度亦在子為玄極者其北方之已極者北  
 之極遠氣下降陰氣上升乃物也死亦有生有天地定氣故玄極亦之也



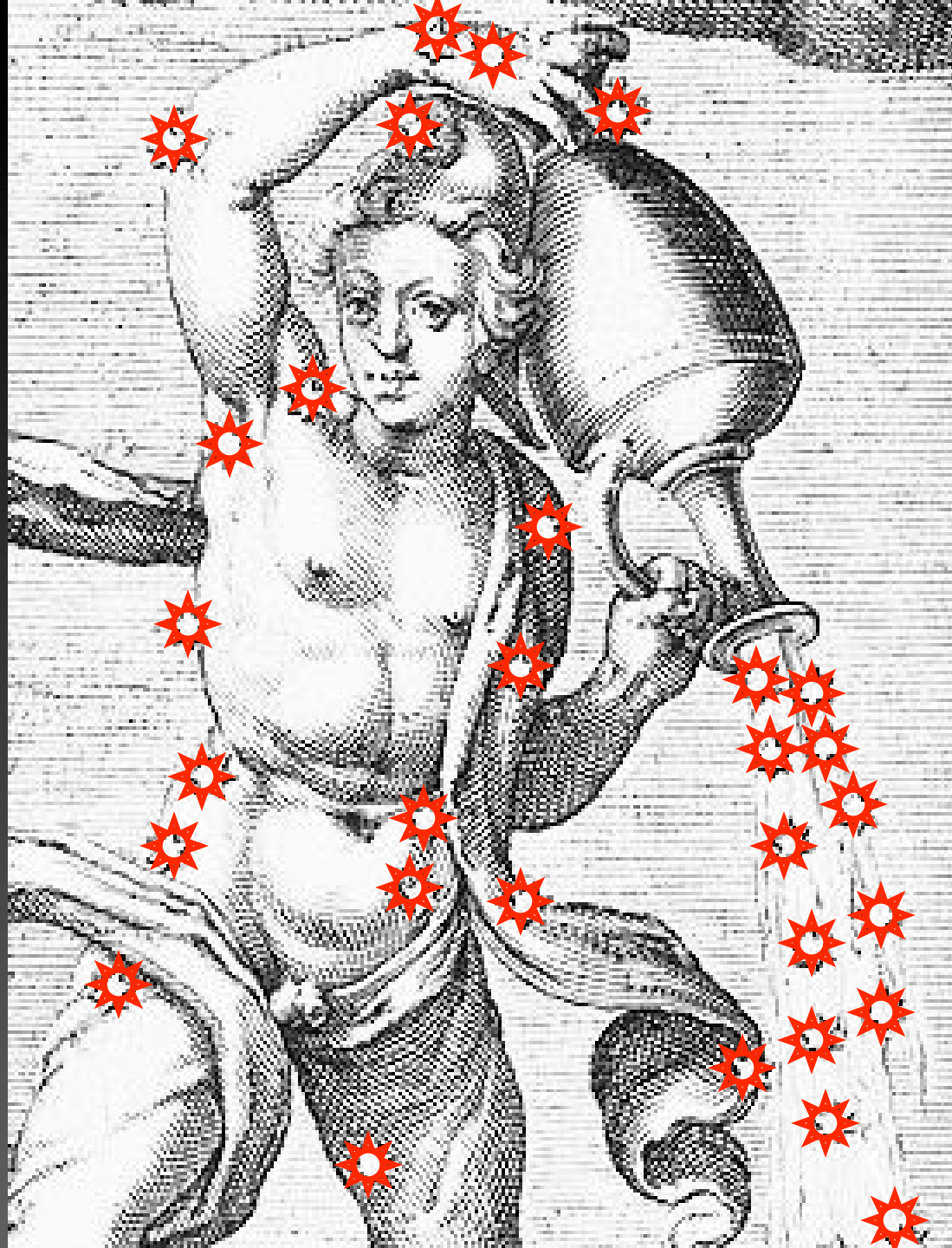
Constellations:

Patterns of  
Stars on the  
Sky





# Aquarius



Aquarius



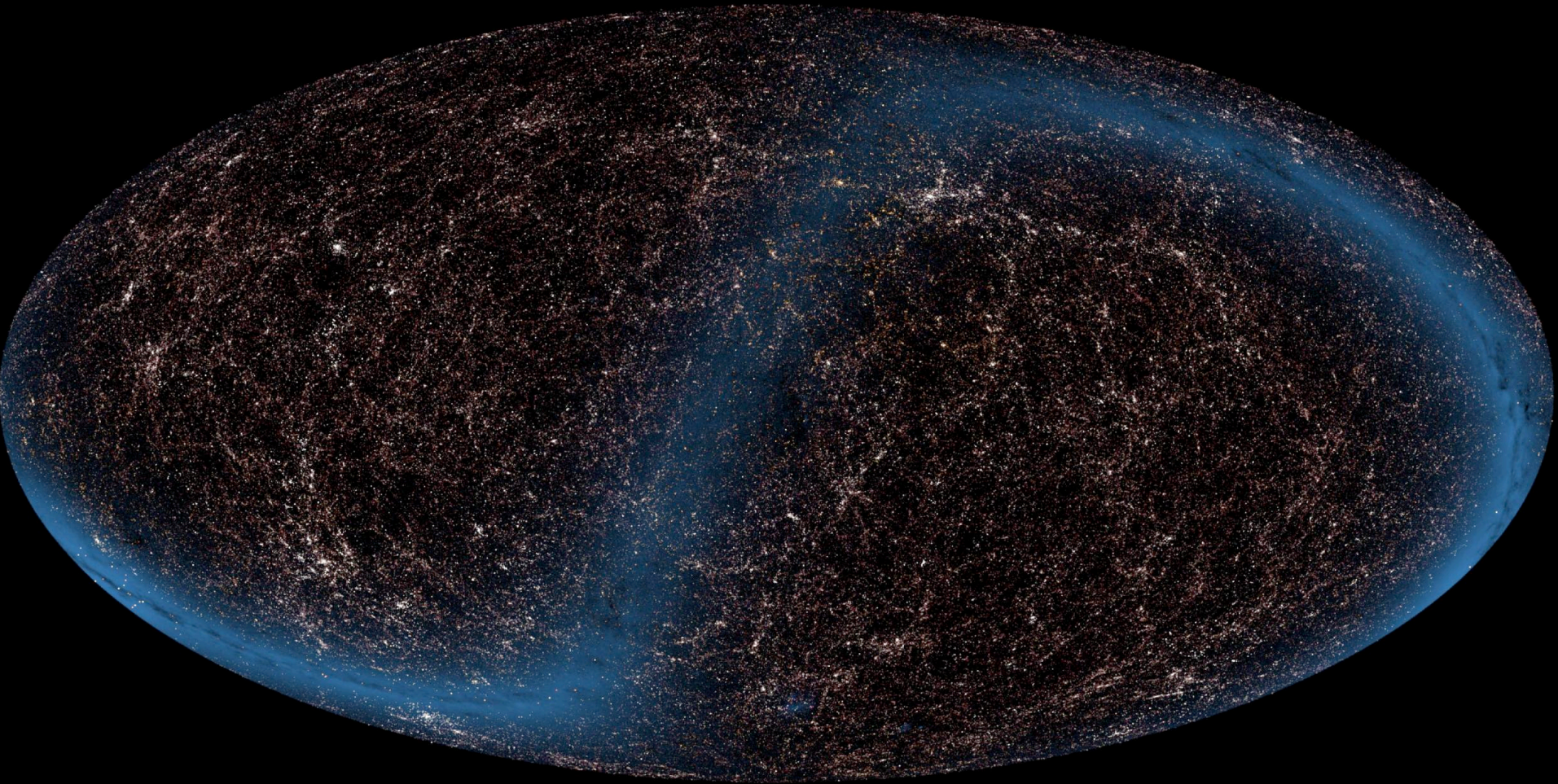


Perseus cluster:  
A 'Constellation' of galaxies



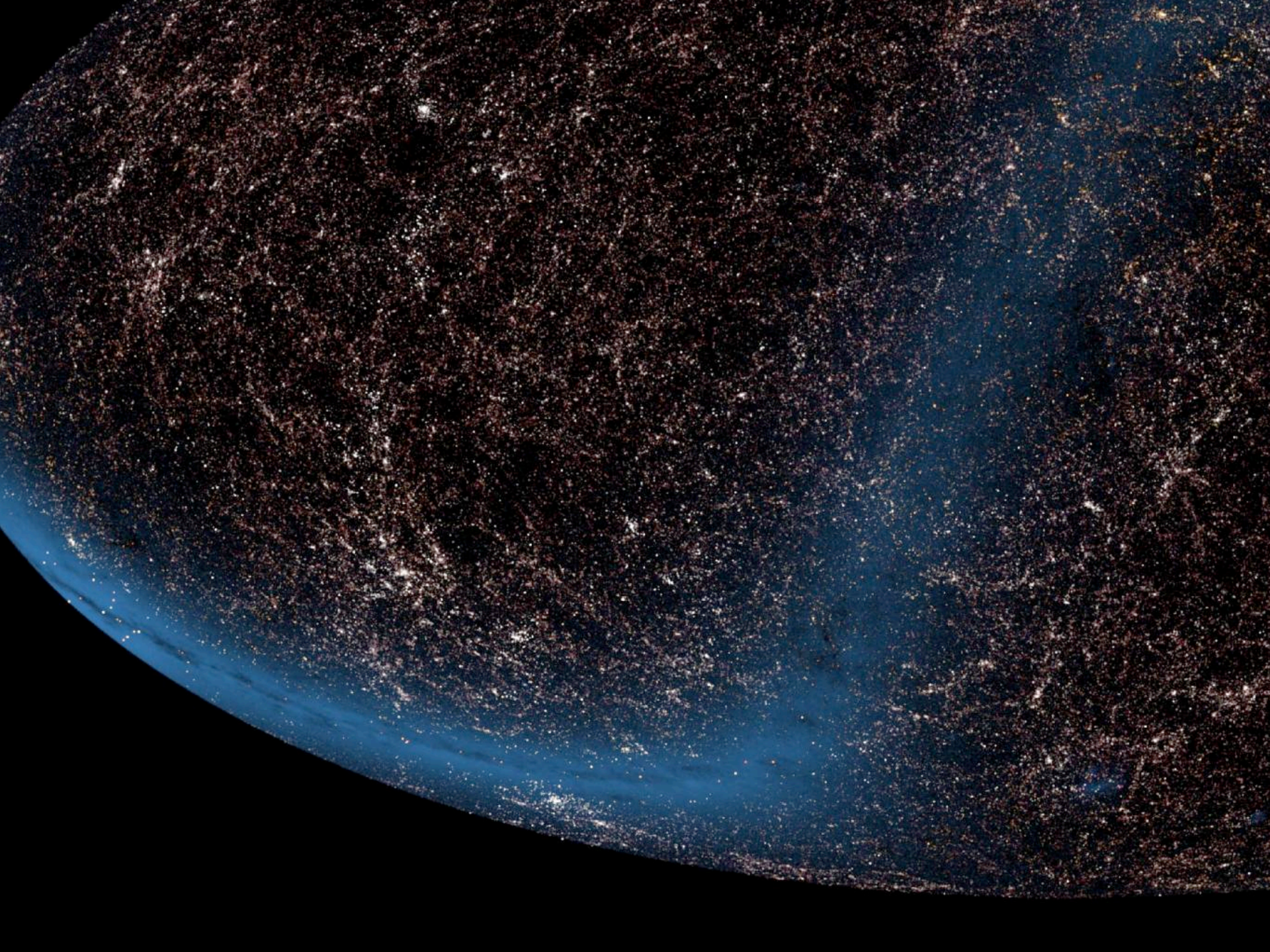


# 2MASS Infrared Sky Survey

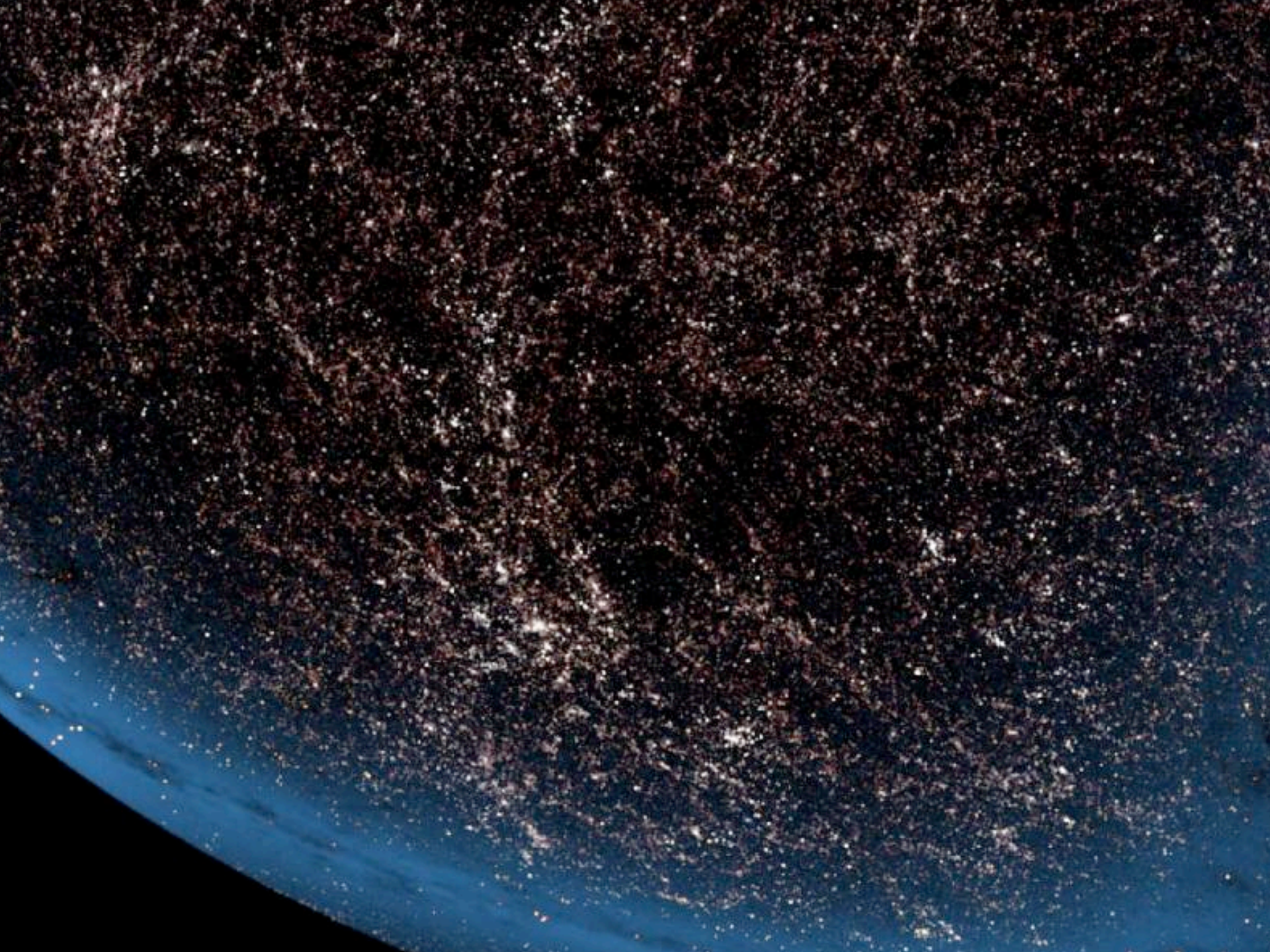


Large-scale Structure: patterns in the distribution of galaxies

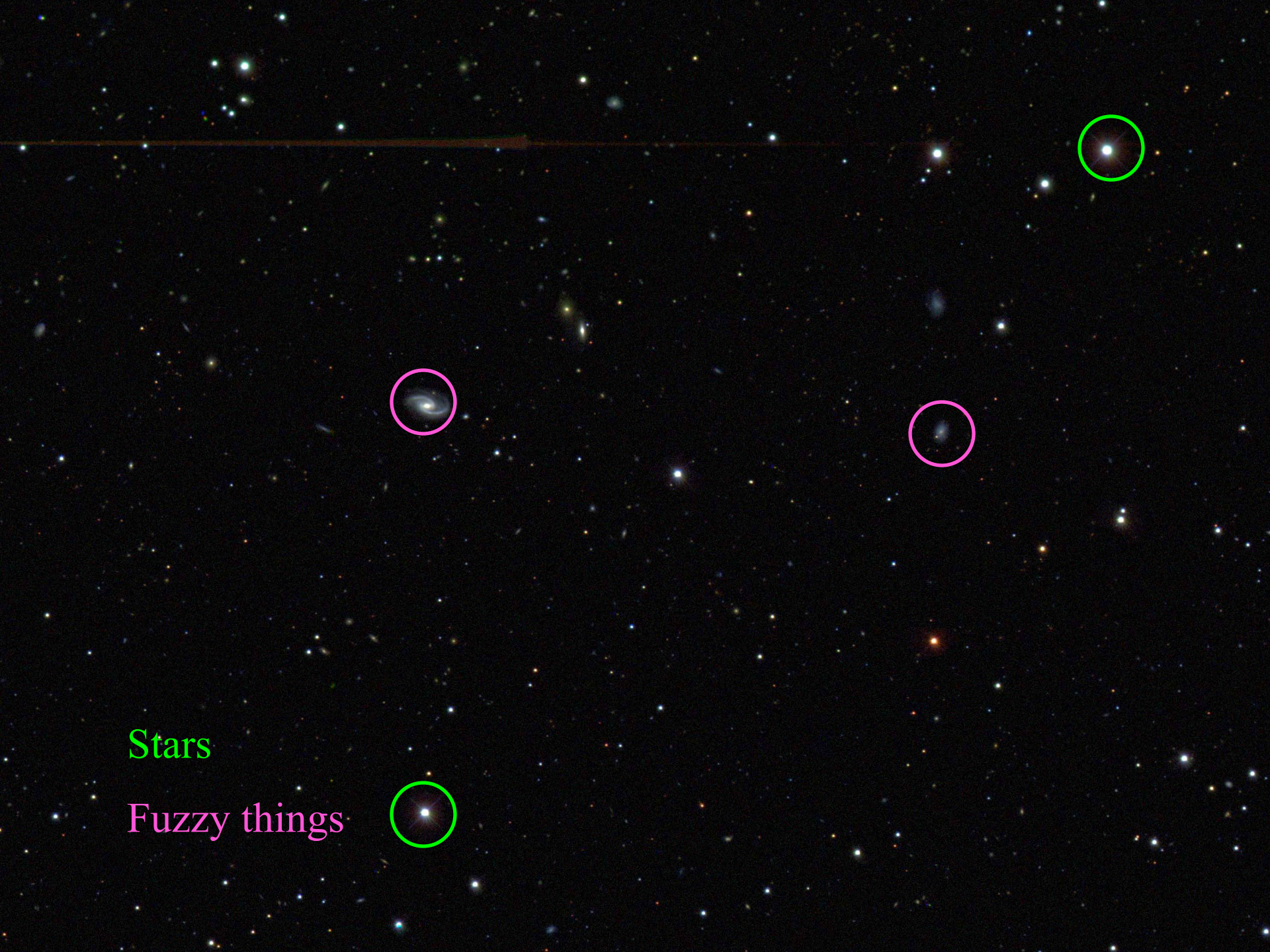












Stars

Fuzzy things



# Charles Messier (1730-1817)



Astronomer for French Navy

Discovered 20 comets

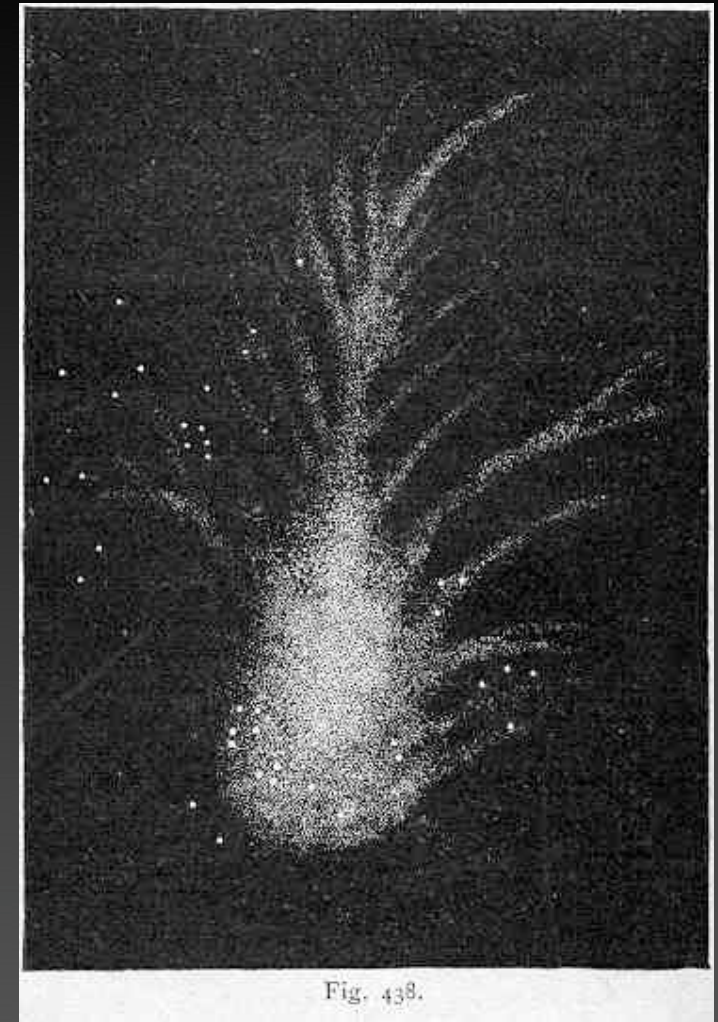
In the course of his search for comets, he catalogued fuzzy things that didn't move:

110 nebulae and star clusters

# Messier 1

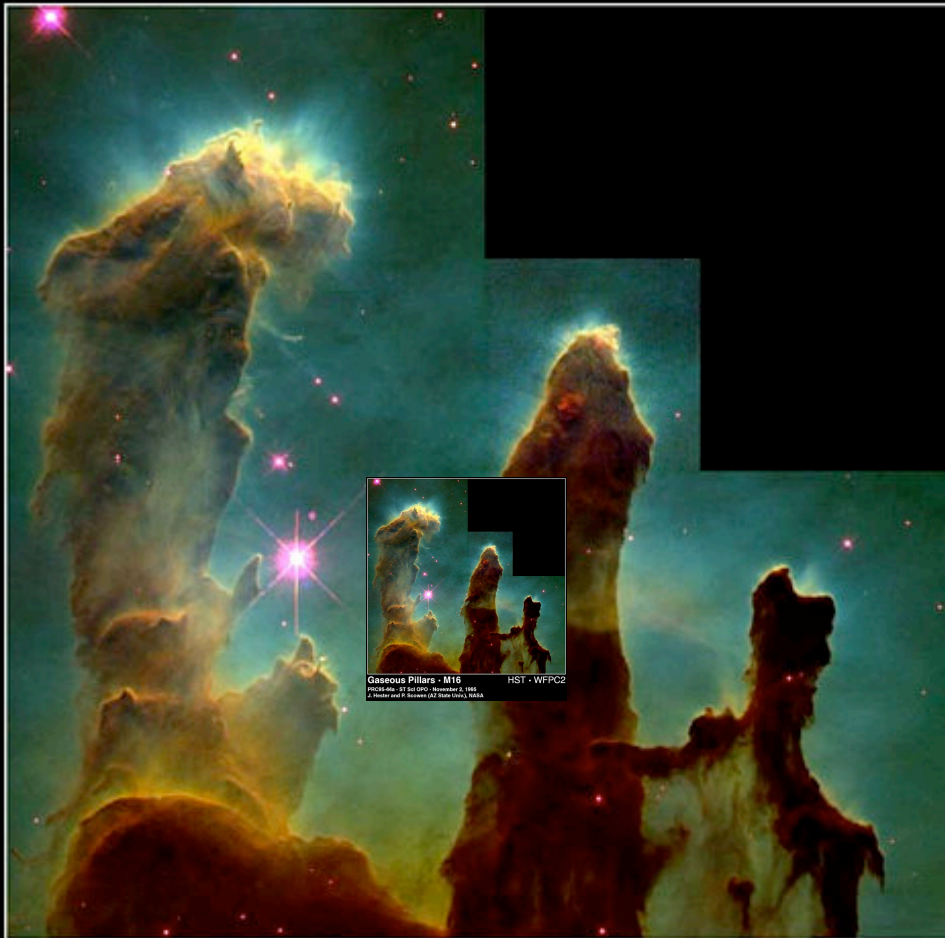


Remnant of Supernova of 1054,  
observed by Chinese and possibly  
by the Anasazi



Drawing by Lord Rosse  
c. 1844

**M16, the Eagle Nebula:**  
clouds of gas & dust that  
are forming new stars

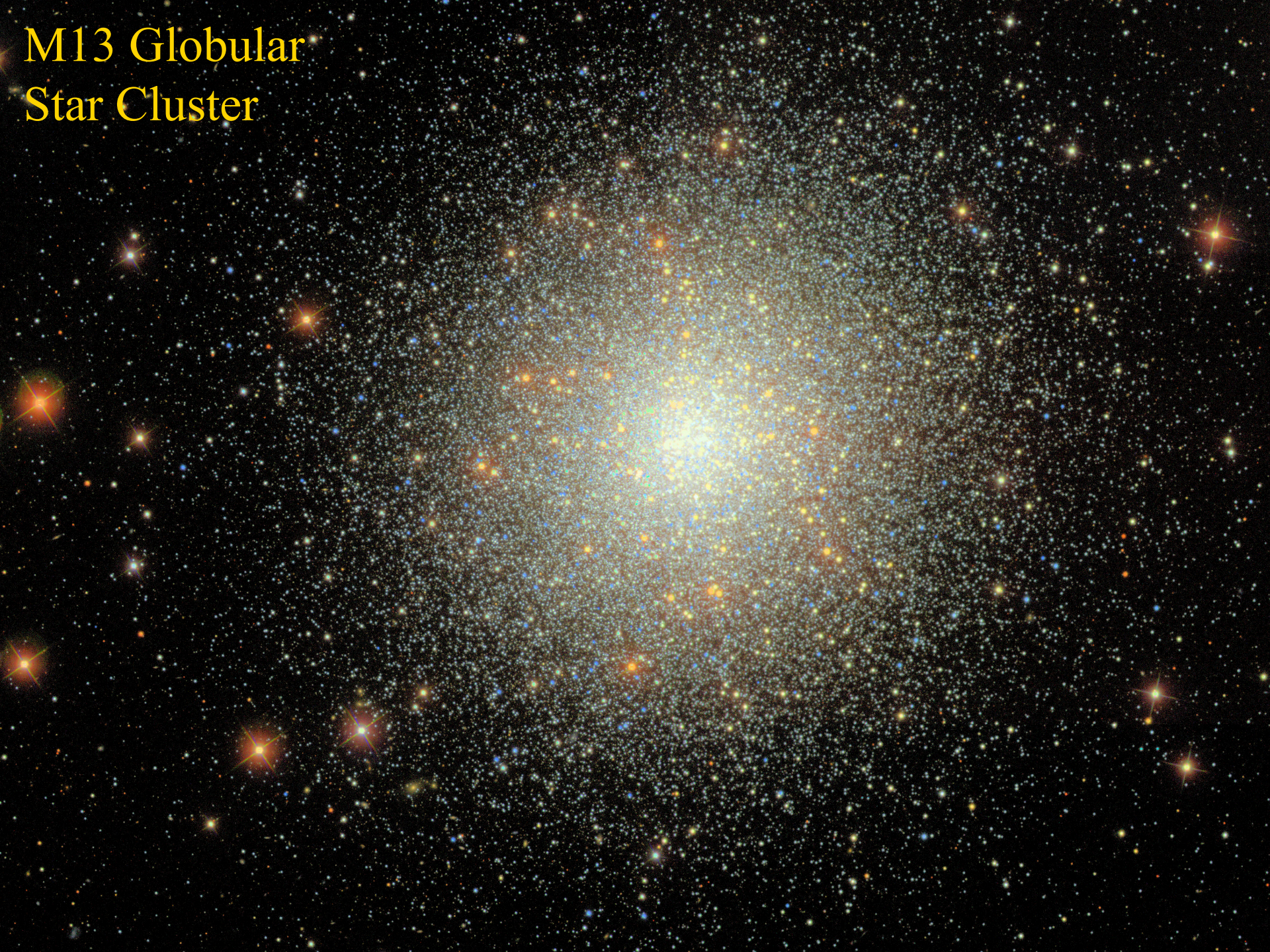


**Gaseous Pillars · M16**

**HST · WFPC2**

PRC95-44a · ST ScI OPO · November 2, 1995  
J. Hester and P. Scowen (AZ State Univ.), NASA





M13 Globular  
Star Cluster



# John Herschel

1792-1871



Mathematician,  
Musician, Lawyer,  
Astronomer,  
Photographer, ...



John Herschel  
1792-1871

*Catalogue of  
Nebulae and Clusters*

Based on observations  
over 4 years at  
Capetown, South Africa  
with his own 20-foot  
telescope



John Herschel  
1792-1871

After a lifetime in  
Astronomy...

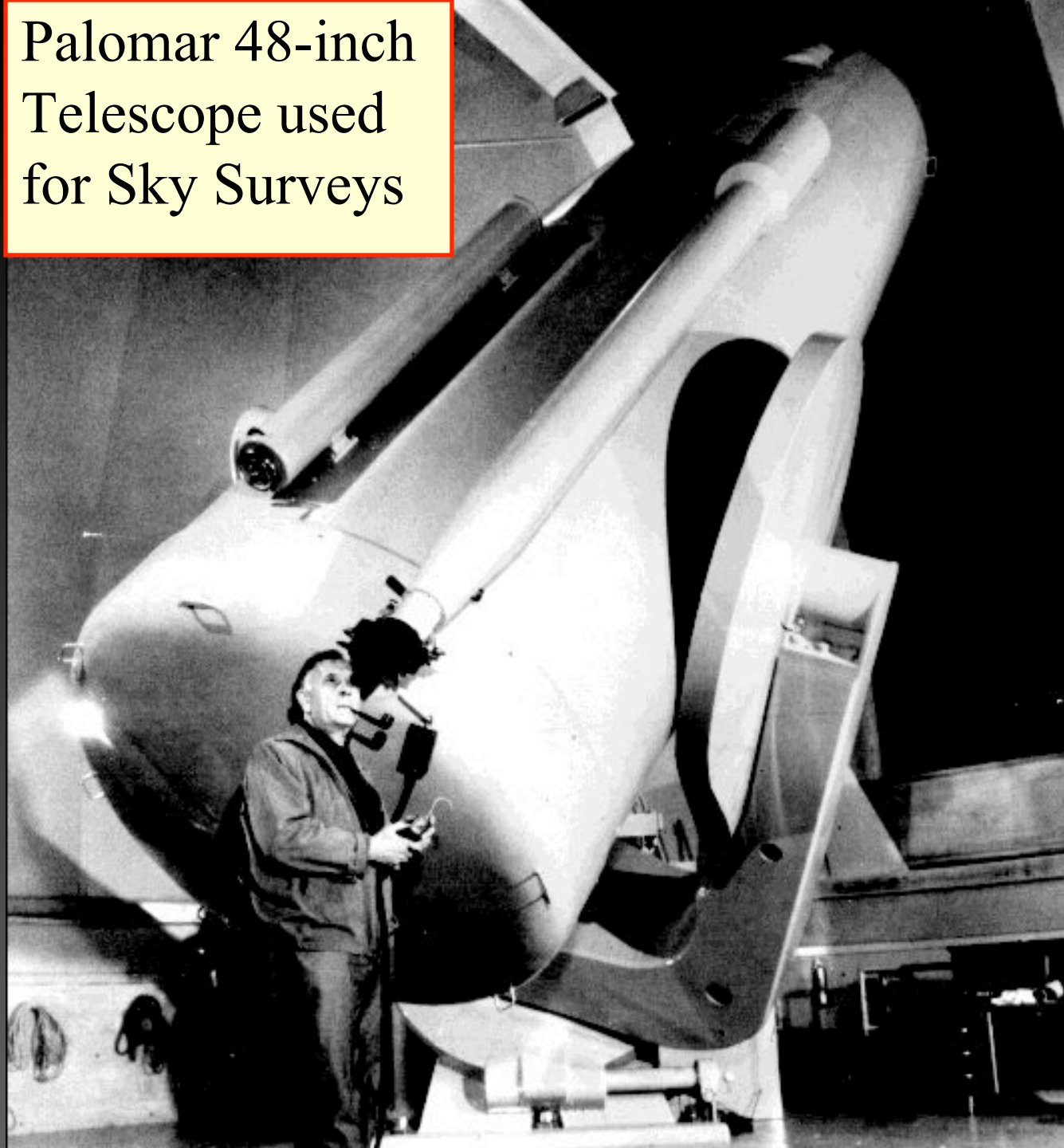
Edwin Hubble  
(1889-1953)

Lawyer,  
Astronomer,  
Boxer

Proved that  
Spiral nebulae are  
galaxies outside  
the Milky Way

Discovered the  
Expanding  
Universe

Palomar 48-inch  
Telescope used  
for Sky Surveys

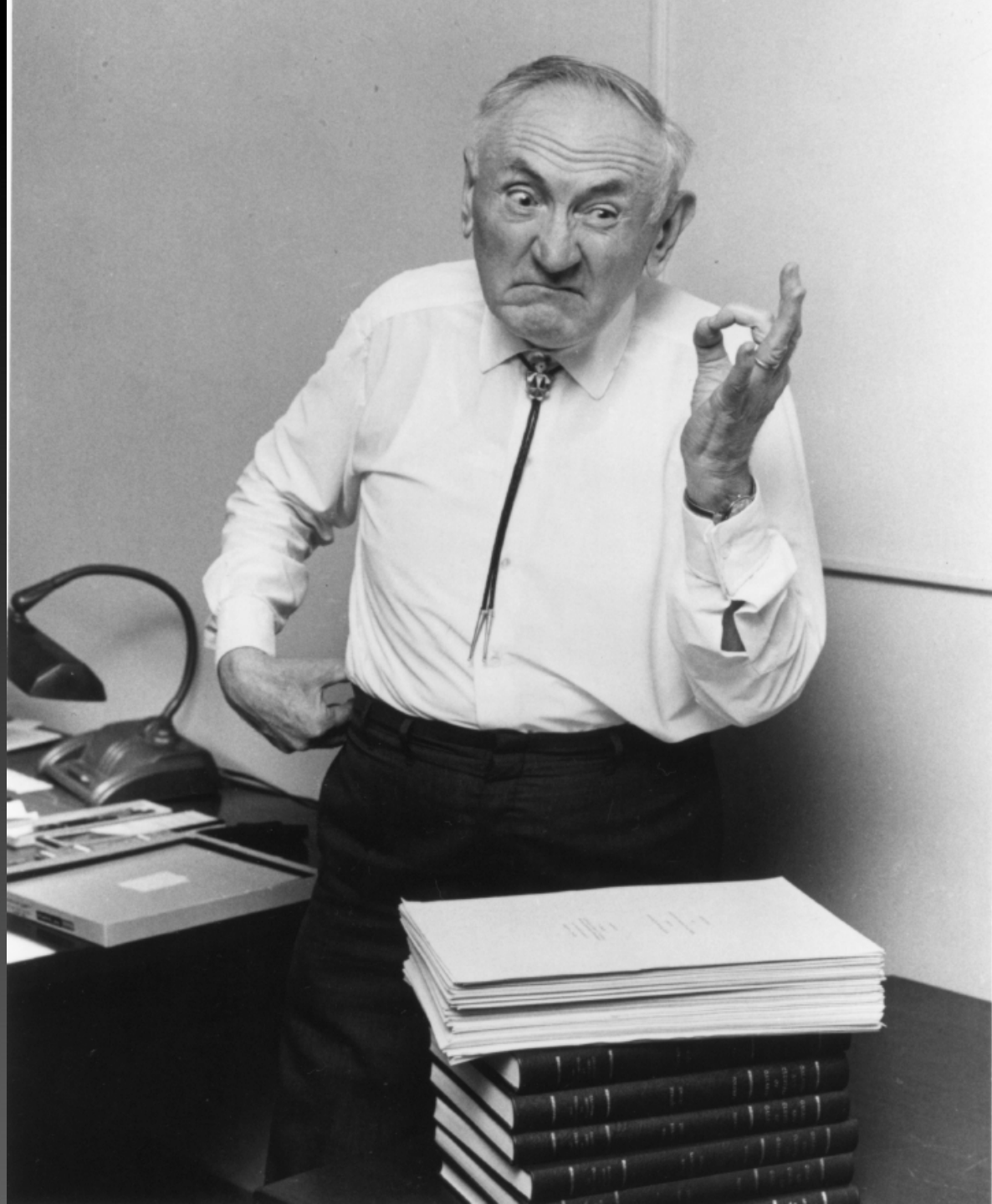


Fritz Zwicky  
(1898-1974)

Astronomer,  
eccentric  
personality

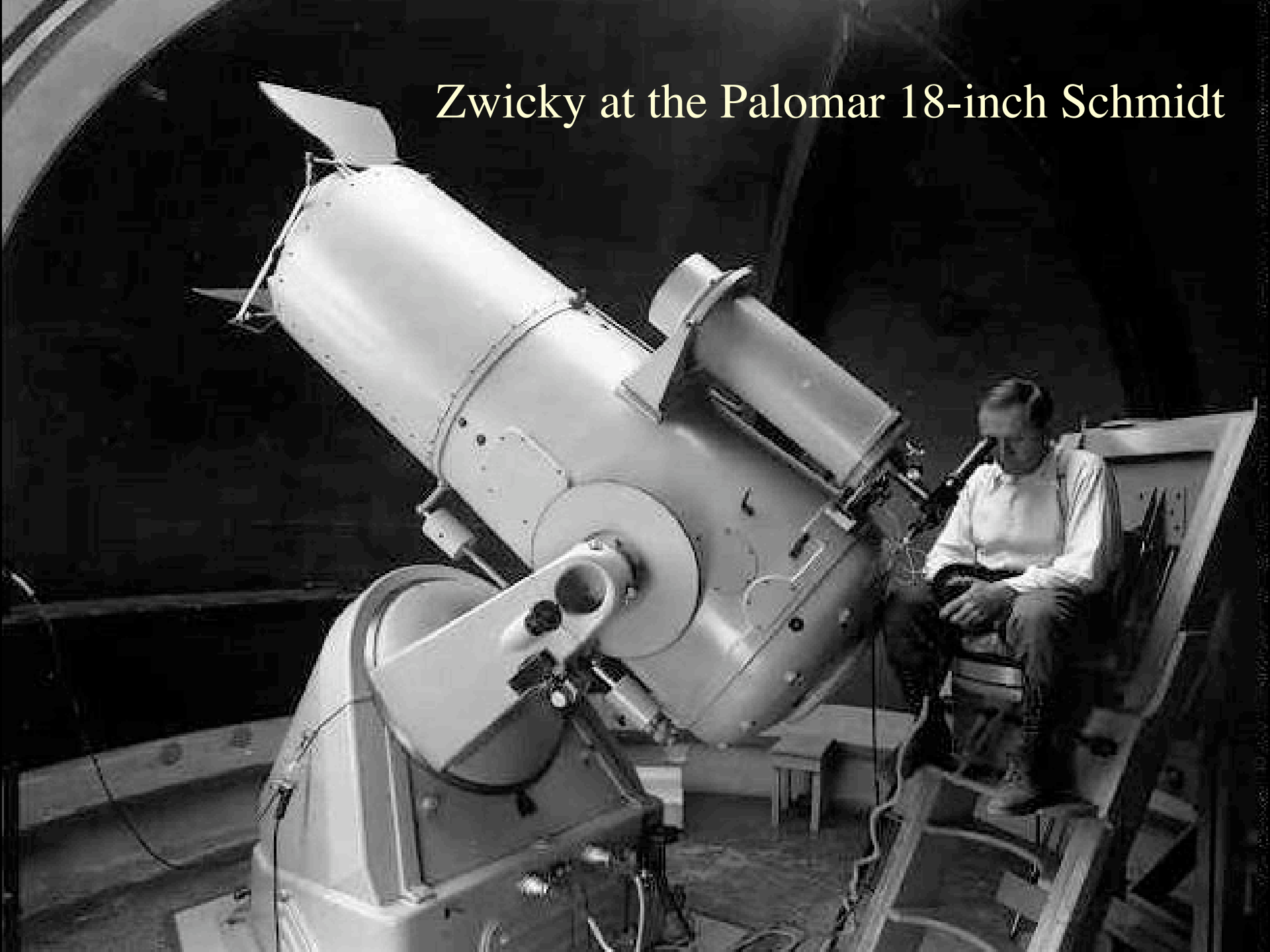
Pioneer of modern  
Sky Surveys

Discoverer of  
Dark Matter,  
Neutron stars,...





# Zwicky at the Palomar 18-inch Schmidt



# Sloan Digital Sky Survey (SDSS)

Dedicated  
2.5-meter  
Telescope

International  
consortium of  
~200 astronomers:

Changing the way  
Astronomy is done



# Progress in Sky Surveys

- The advent of telescopes led astronomers to find & catalog non-stellar objects: nebulae and clusters (Messier, Dunlop, Herschels, Dreyer's NGC, ...)
- Advances in telescope optics and photography led to deeper catalogs covering larger portions of the sky (e.g., Schmidt telescopes with large fields of view)
- Recent advances in detector technology (CCDs) and computing power have ushered in the new age of digital sky surveys.

1780--Messier: 110 objects      2005--SDSS: 100,000,000



# The Universe Observed

The Universe contains a  
hierarchy of structure...

# Human scale:

Size  $\sim$  100 centimeters

Mass  $\sim$  100 kilograms

Sarah &  
Helen Frieman

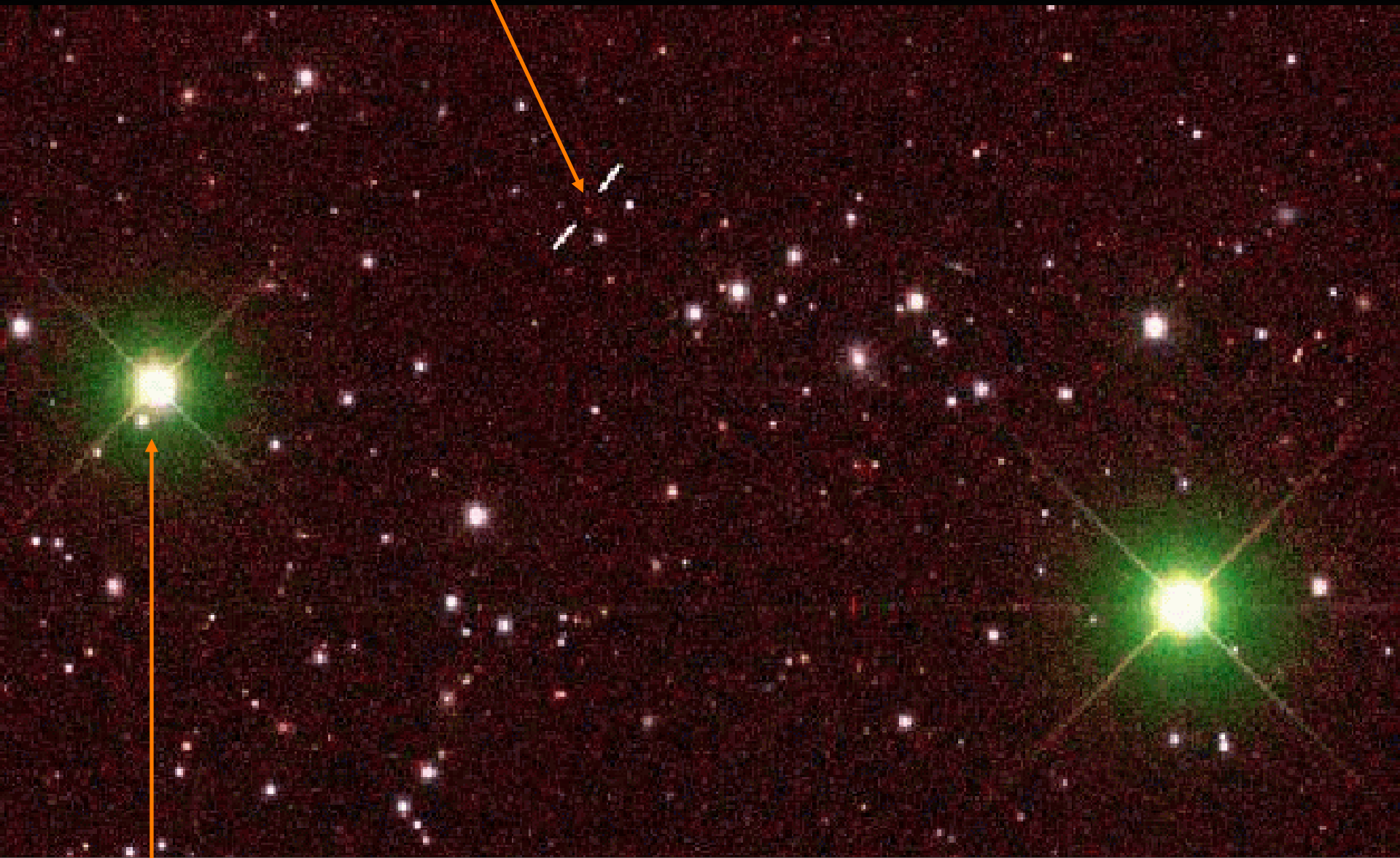




**Planets:** Size  $\sim$  10 billion centimeters  
Mass  $\sim 10^{26}$  kilograms



# Brown Dwarf Star (Planet/star transition)



Ordinary Stars: Size  $\sim 100$  billion cm    Mass  $\sim 10^{30}$  kilograms

Hot gas bound by gravity



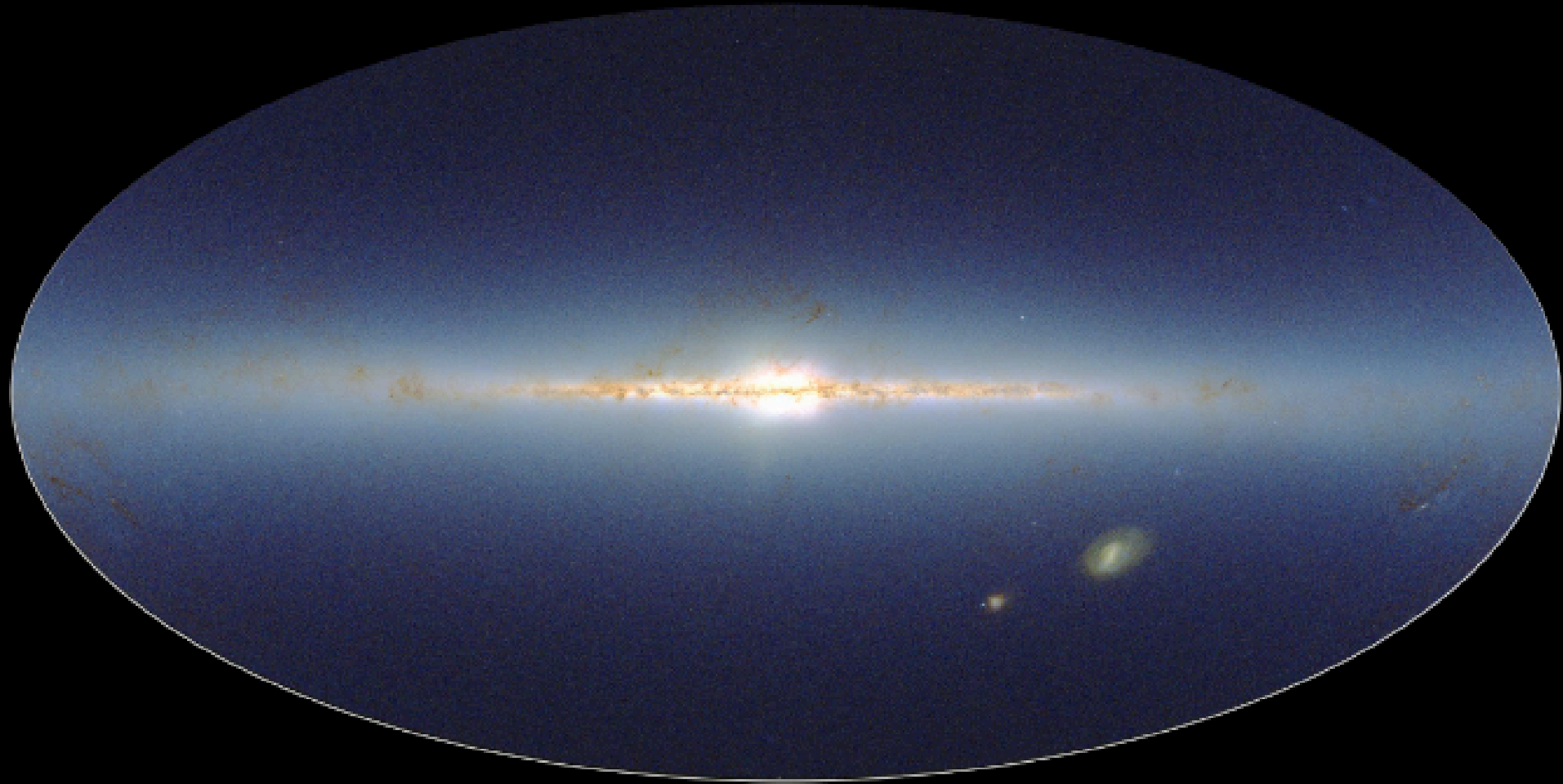
# M87 Nebula in Orion constellation

Interstellar gas  
clouds & star clusters:

Size  $\sim 3$  light-years  
 $\sim 3 \times 10^{18}$  cm  
 $\sim 18$  trillion miles

Mass  $\sim 100,000 M_{\text{sun}}$

# An Infrared view of the **Milky Way** (our galaxy)



**Galaxies:** Size  $\sim 10^{22}$  cm  $\sim$  60,000 light-years    Mass  $\sim$  1 trillion  $M_{\text{sun}}$   
Self-gravitating systems of stars, gas, and dark matter





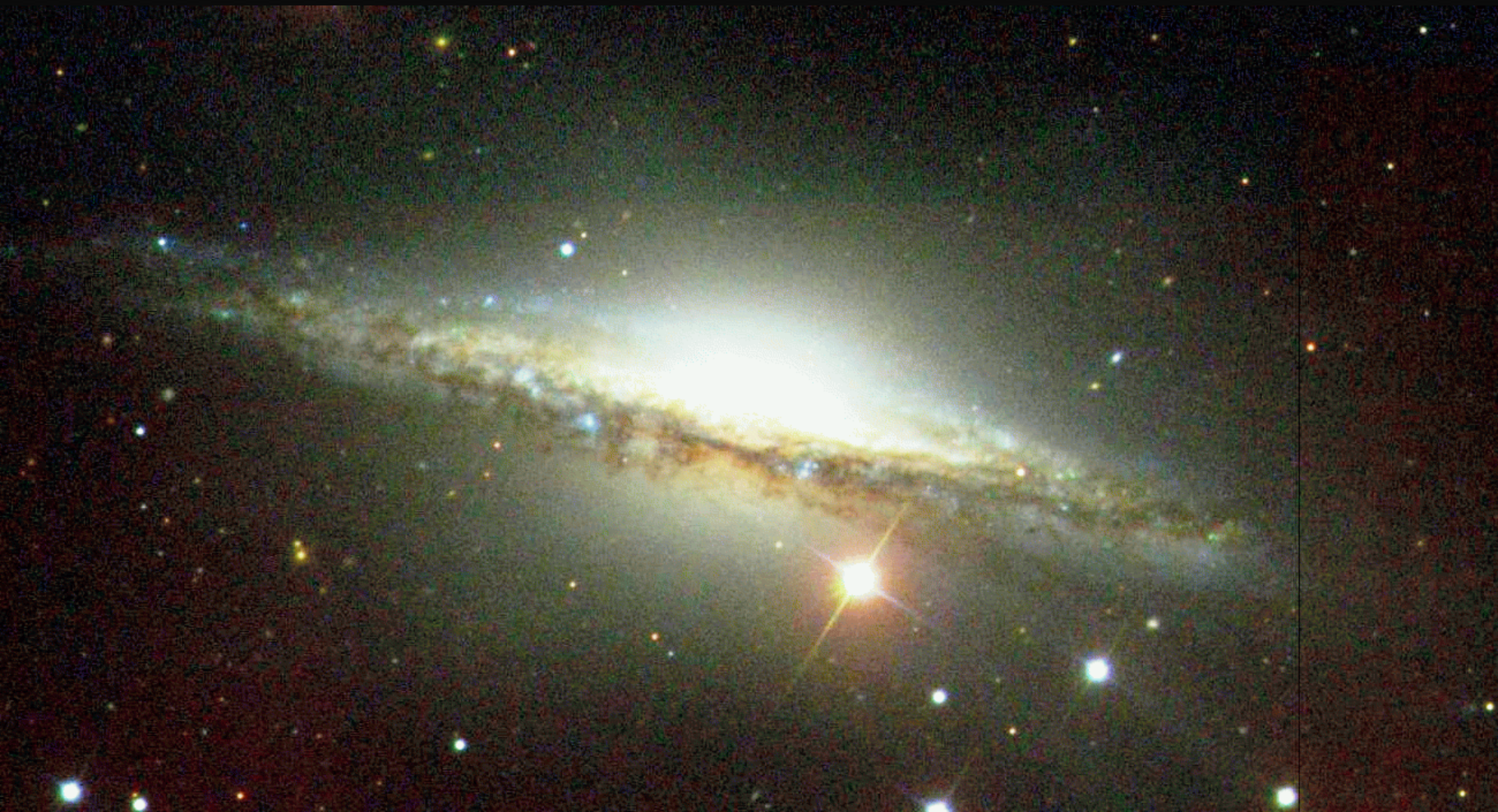
M101





M109















UGC 03214: edge-on galaxy in Orion





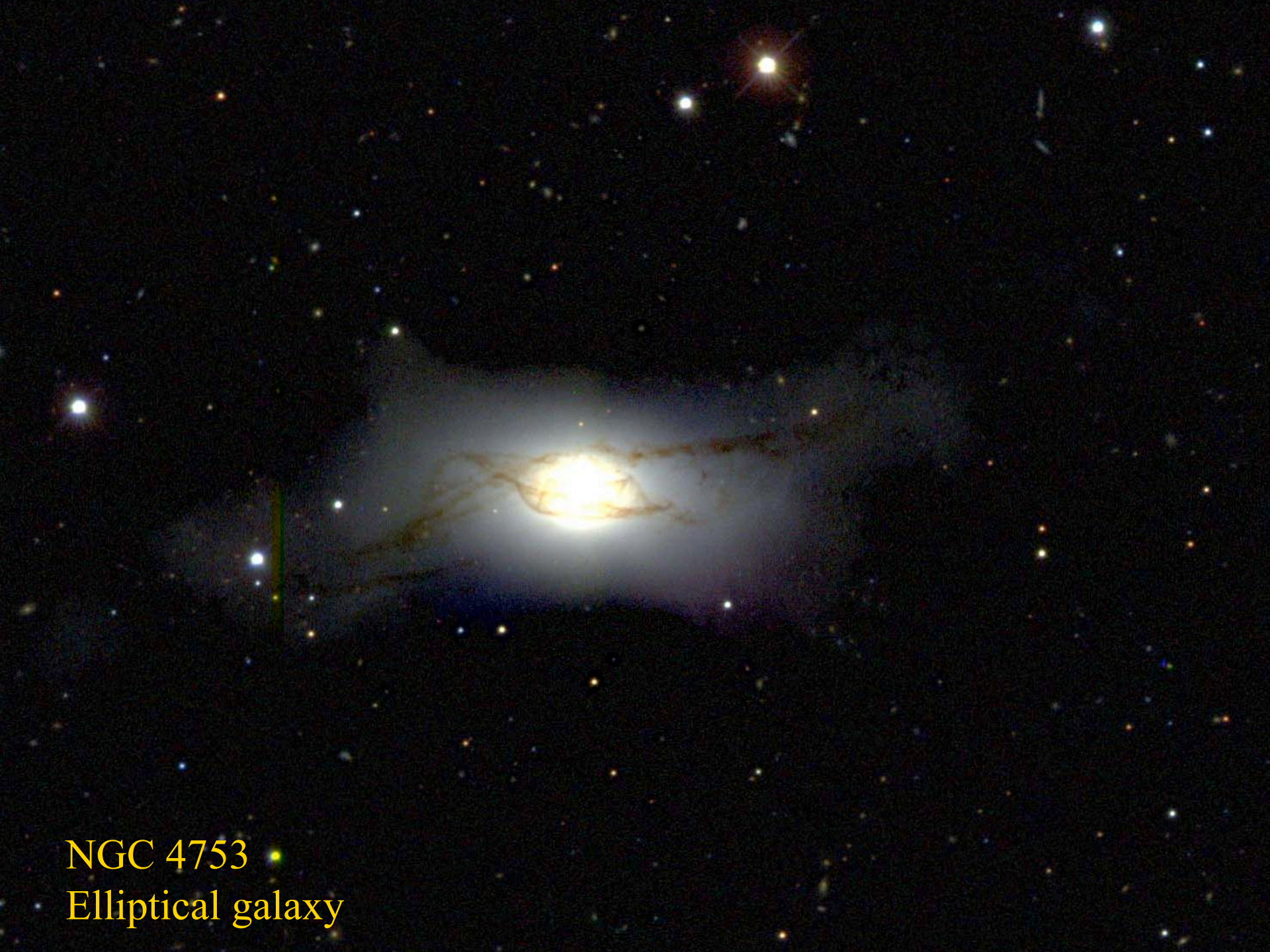






M82





NGC 4753  
Elliptical galaxy

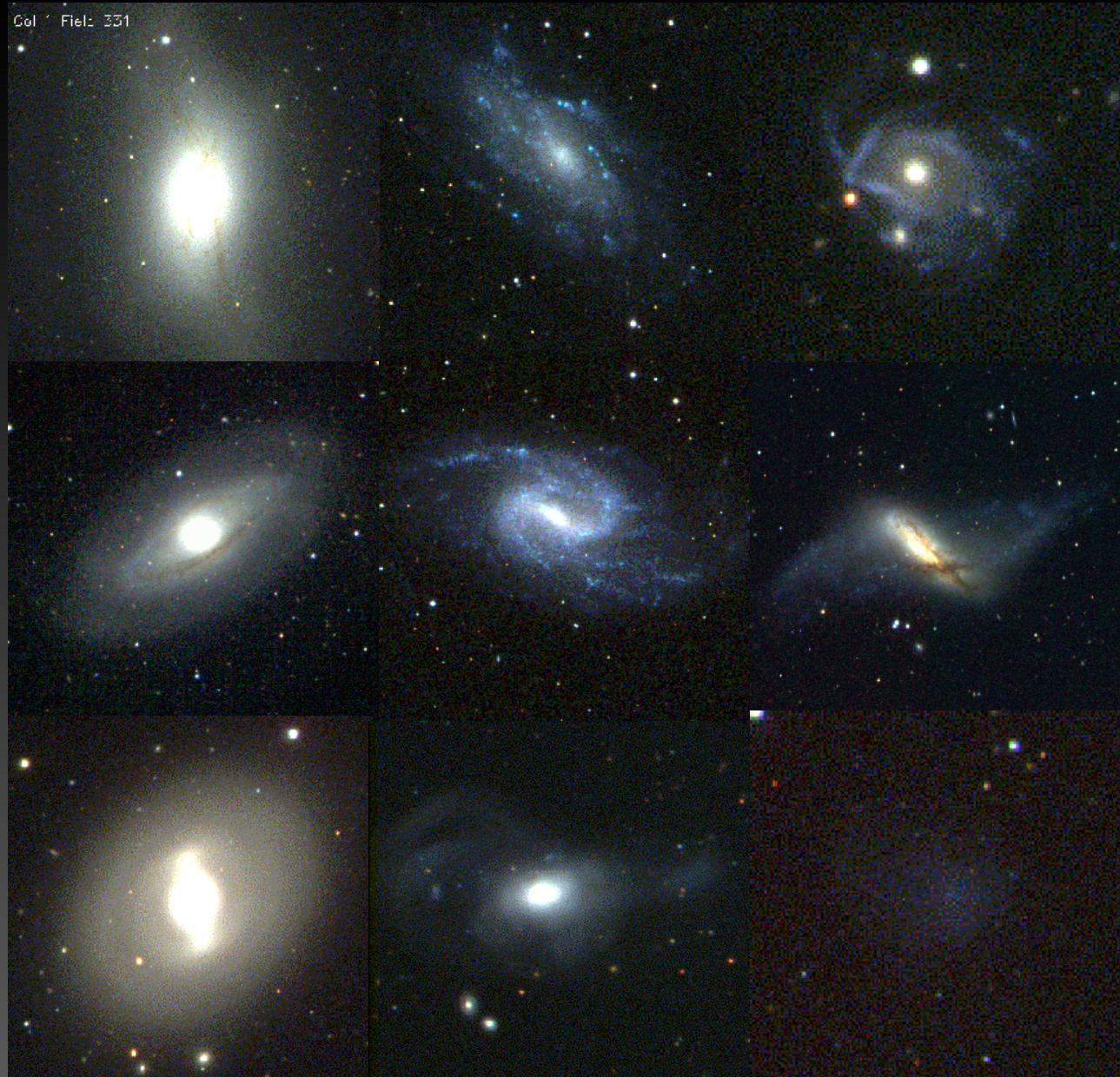




M87  
Elliptical galaxy



Galaxies come in  
a variety of  
shapes, sizes,  
colors, and  
luminosities





# Galaxy Mergers & Acquisitions









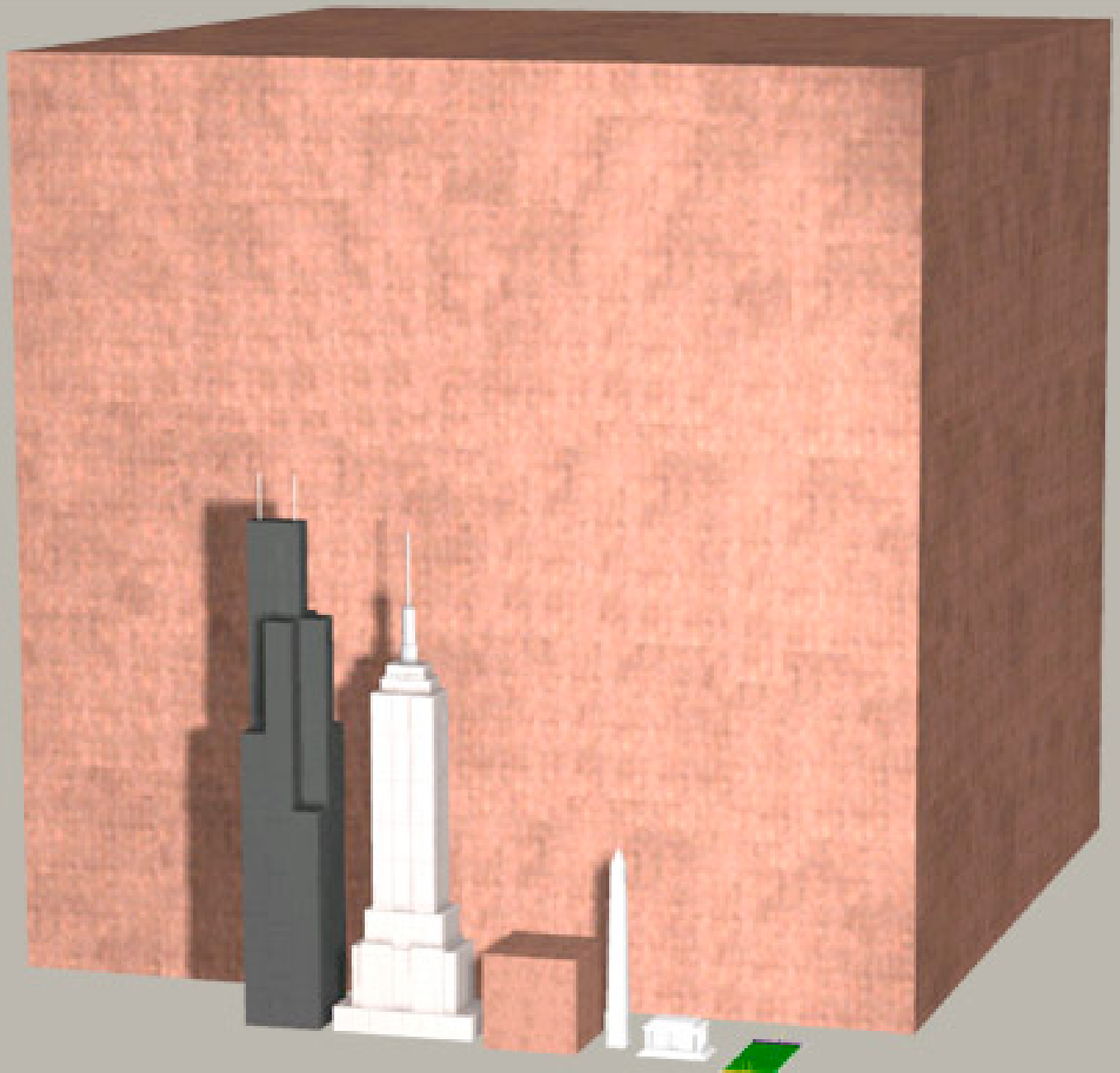
**Clusters of Galaxies:** Size  $\sim$  few Million light years

Mass  $\sim$  1 quadrillion (1000 x 1 trillion)  $M_{\text{sun}}$

Largest bound systems, they contain: galaxies, gas, dark matter

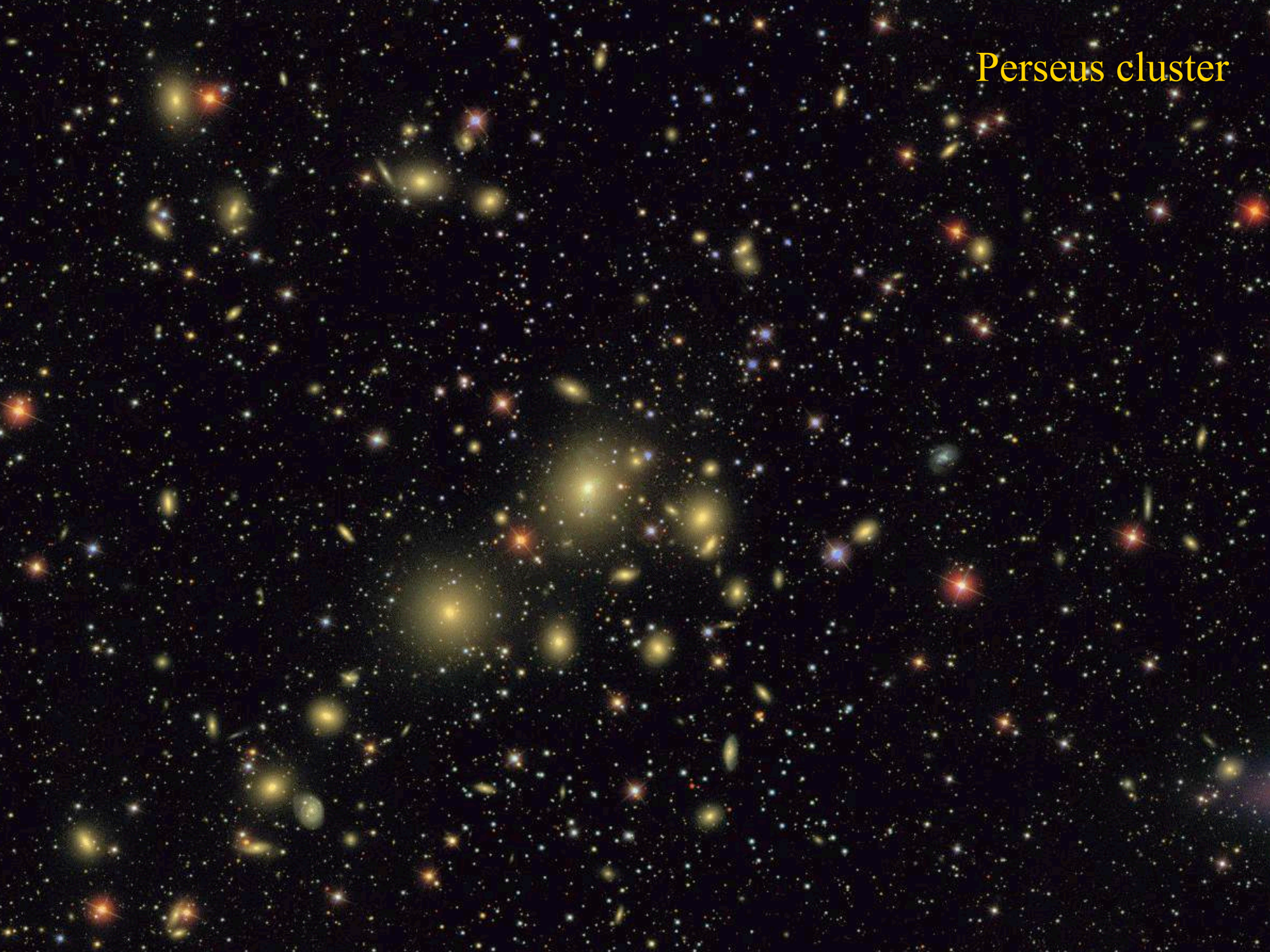


One  
Quadrillion  
pennies





Perseus cluster

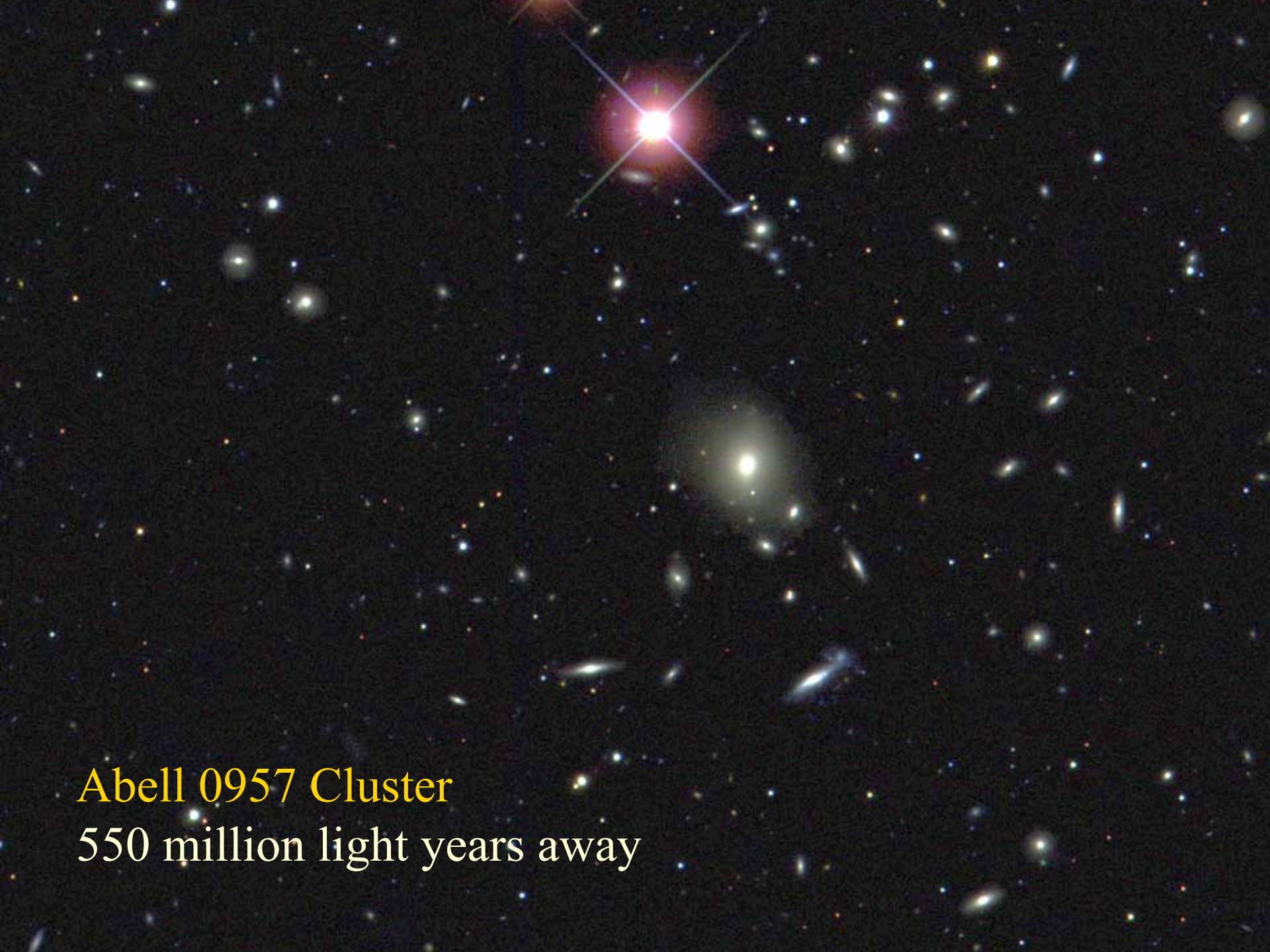






Abell 2199





Abell 0957 Cluster

550 million light years away





Abell 2255 Cluster  
1 billion light years





New SDSS cluster  
4 billion light years



More distant  
SDSS Cluster

The Expanding Universe: more distant objects appear redder





# The Expanding Universe

More distant galaxies appear redder



# The Expanding Universe

More distant galaxies appear redder

The amount of color (frequency) change  
is called the Redshift

Redshift of light is like the Doppler shift  
of sound as a train or racecar passes by



R E D S H I F T

[CURRENT  
DESIGNS](#)[FALL 04  
CONCEPTS](#)[ABOUT US](#)

Contemporary Dress Design for Women

# The Expanding Universe

More distant galaxies appear redder.

They are moving away from us, with:

speed (redshift)  $\propto$  distance

(Hubble's Law)



# The Expanding Universe

More distant galaxies appear redder.

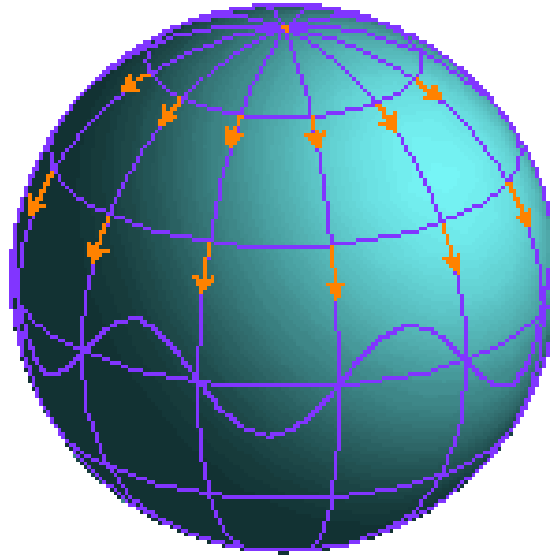
They are moving away from us, with:

$$\text{speed} \propto \text{distance}$$

A galaxy 100 Million light years away is receding from us at 2000 miles per second

We can thus use redshift as a stand-in for distance or for look-back time

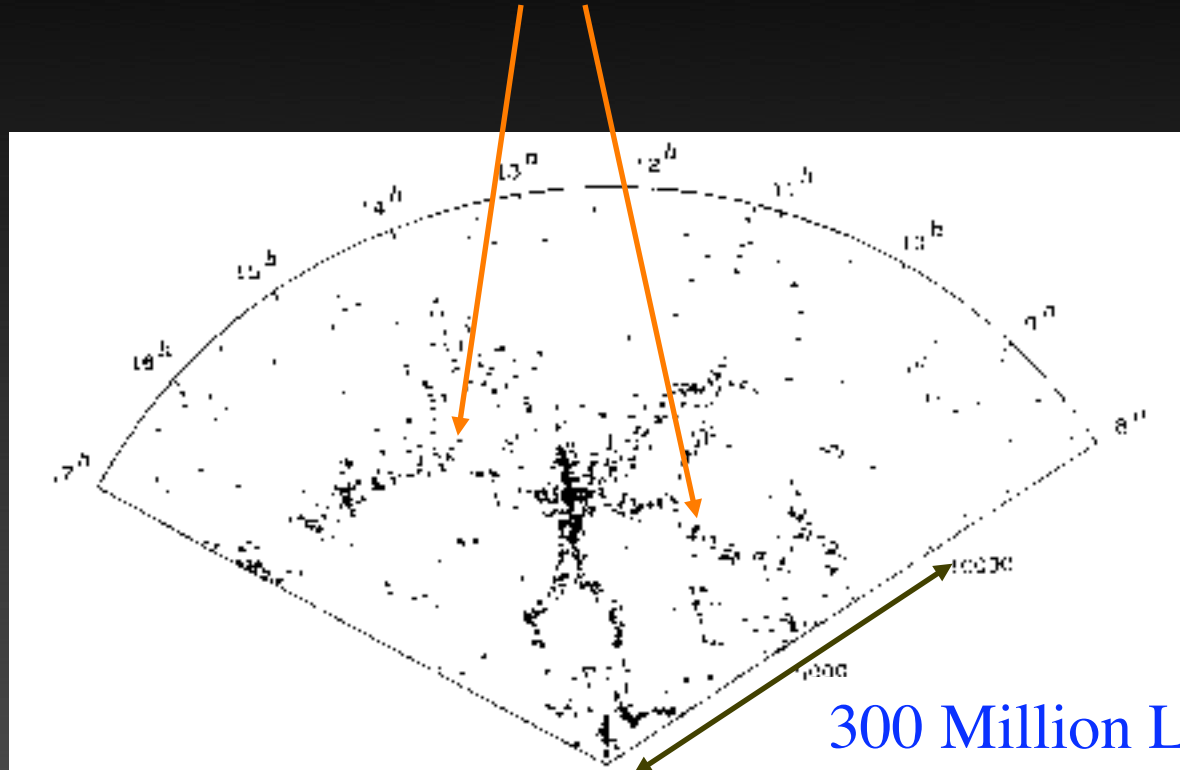
# The Expanding Universe





# Superclusters and Large-scale Structure: Filaments, Walls, and Voids of Galaxies

Center  
for  
Astrophysics  
Redshift  
Survey  
(1986)



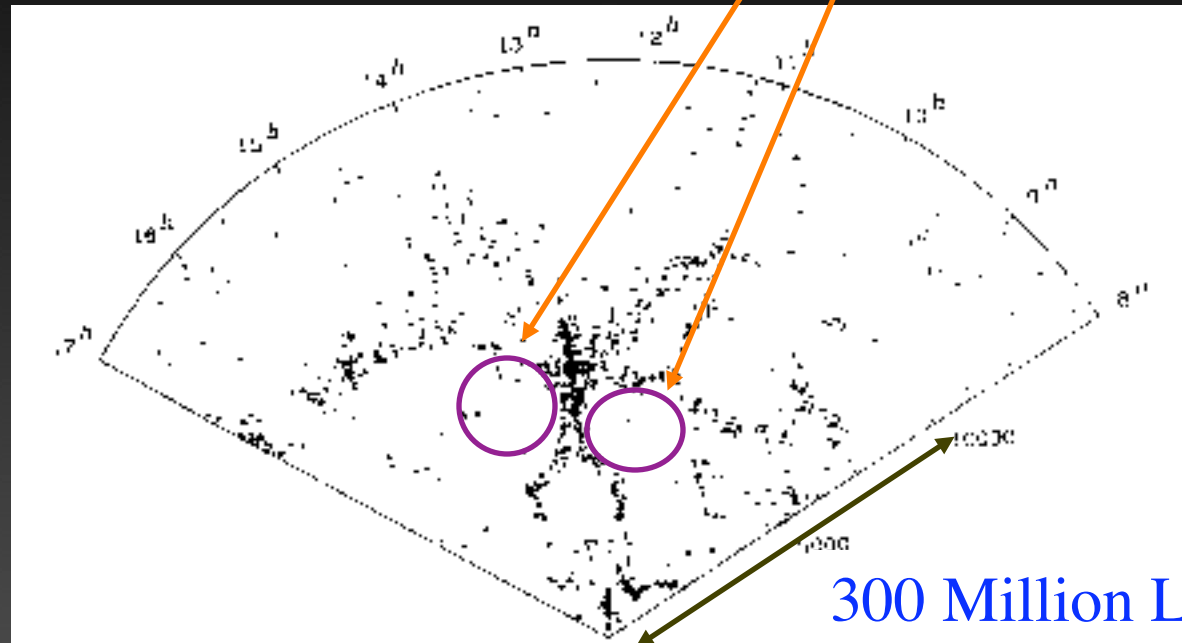
300 Million Light-  
years

‘Watermelon Slice’ 6 degrees thick containing 1060 galaxies:  
position of each galaxy represented by a single dot

Radial coordinate is redshift (much easier to measure than distance)

# Superclusters and Large-scale Structure: Filaments, Walls, and Voids of Galaxies

Center  
for  
Astrophysics  
Redshift  
Survey  
(1986)

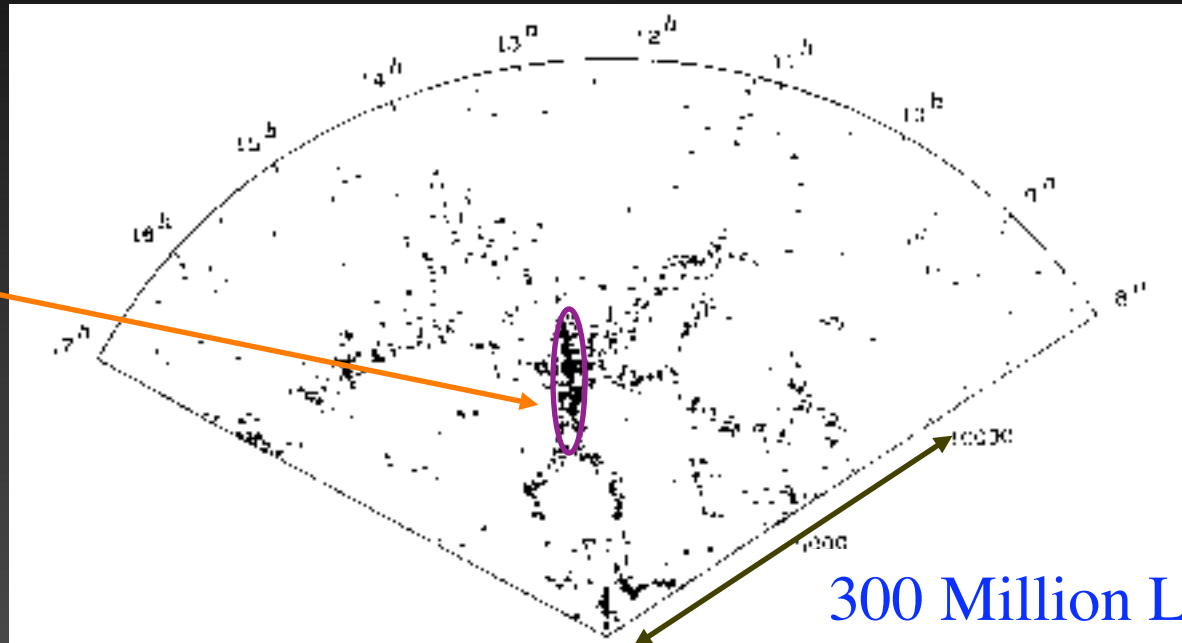


‘Watermelon Slice’ 6 degrees thick containing 1060 galaxies:  
position of each galaxy represented by a single dot



# Superclusters and Large-scale Structure: Filaments, Walls, and Voids of Galaxies

# Coma Cluster of Galaxies: "Finger of God"



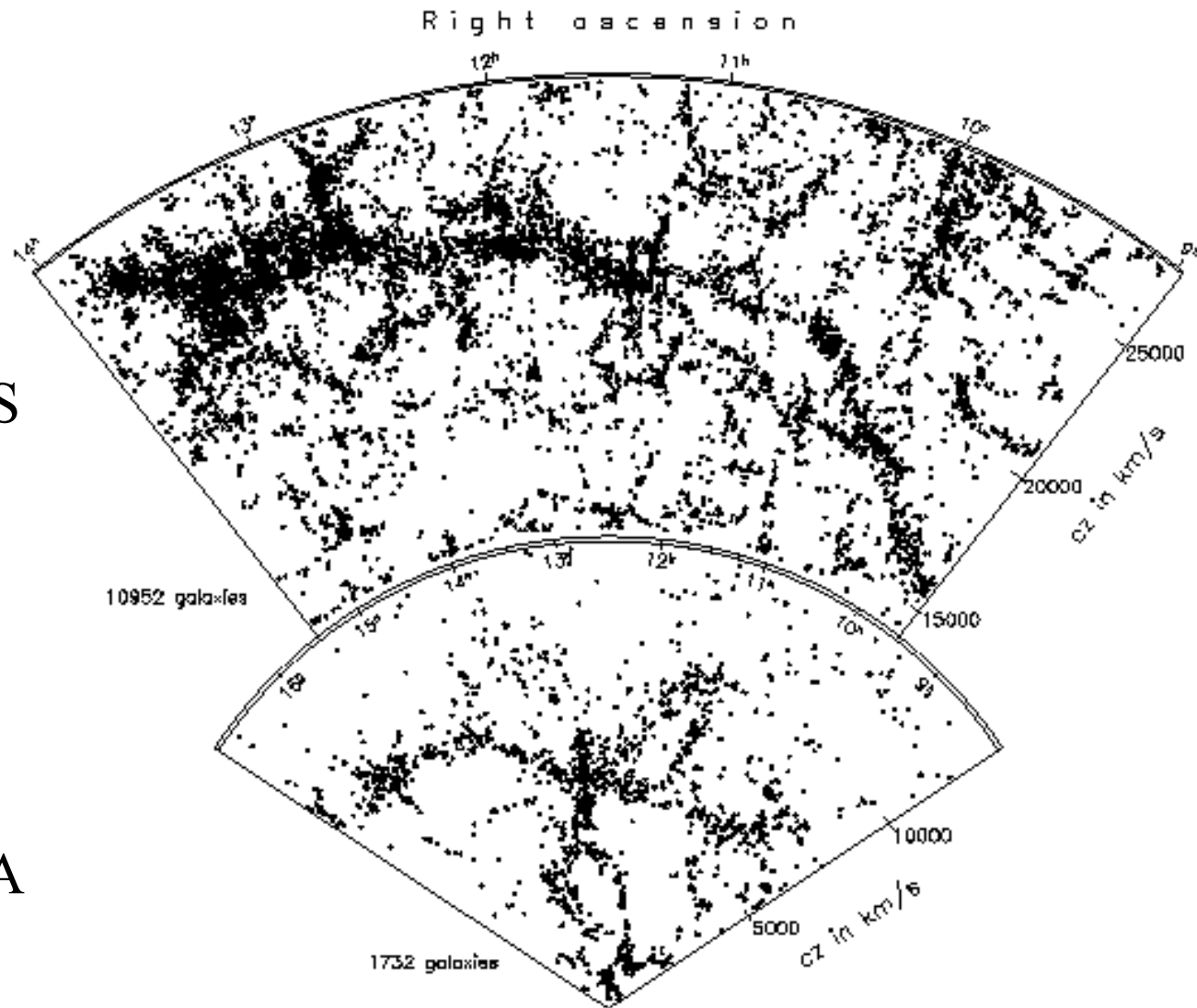
# 300 Million Light-years

# You Are Here

‘Watermelon Slice’ 6 degrees thick containing 1060 galaxies:  
position of each galaxy represented by a single dot

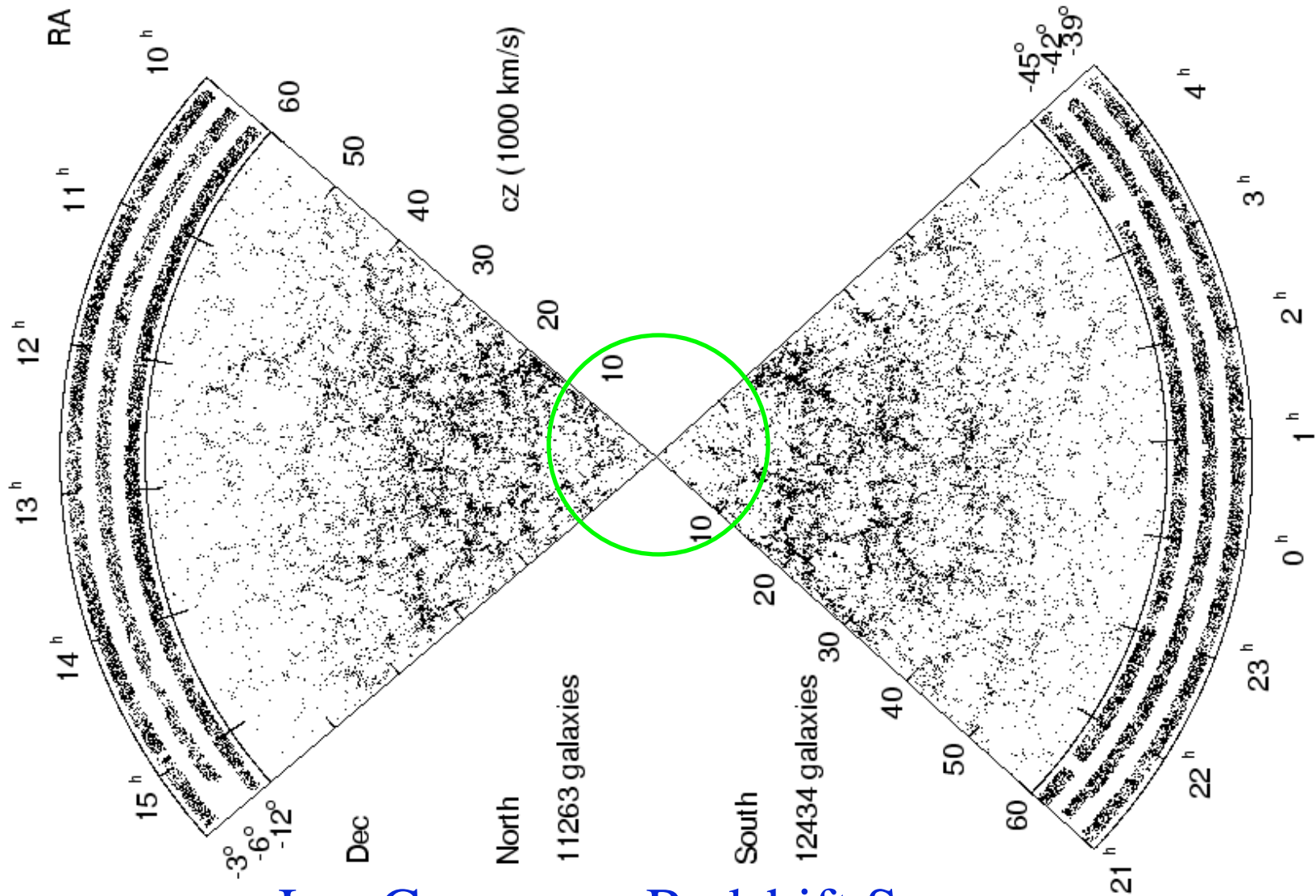
SDSS

CfA





## Scale of CfA survey



# Why Survey the Universe Now?

By determining how the matter of the Universe is distributed in space, we can help address some basic questions in cosmology:



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How did galaxies and large-scale structures form?

# Why Survey the Universe Now?

By determining how the matter of the Universe is distributed in space, we can help address some basic questions in cosmology:

How did galaxies and large-scale structures form?

What is the Universe made of?

**DARK MATTER**  
**DARK ENERGY**



# Why Survey the Universe Now?

By determining how the matter of the Universe is distributed in space, we can help address some basic questions in cosmology:

How did galaxies and large-scale structures form?

What is the Universe made of?

What happened in the earliest moments of the Big Bang?

# The Big Bang Theory

The Universe has been expanding from a hot, dense  
`beginning' for about 14 billion years

Only successful framework for several key facts  
about the Universe:

- Hubble's law of galaxy recession: expansion
- Isotropy of Cosmic Microwave background
- Cosmic abundances of the light elements  
cooked in the first 3 minutes
- Paradigm for Structure Formation



# Padres Use Big-Bang Theory to Beat Mets

Mets	5
Padres	12

By BUSTER OLNEY

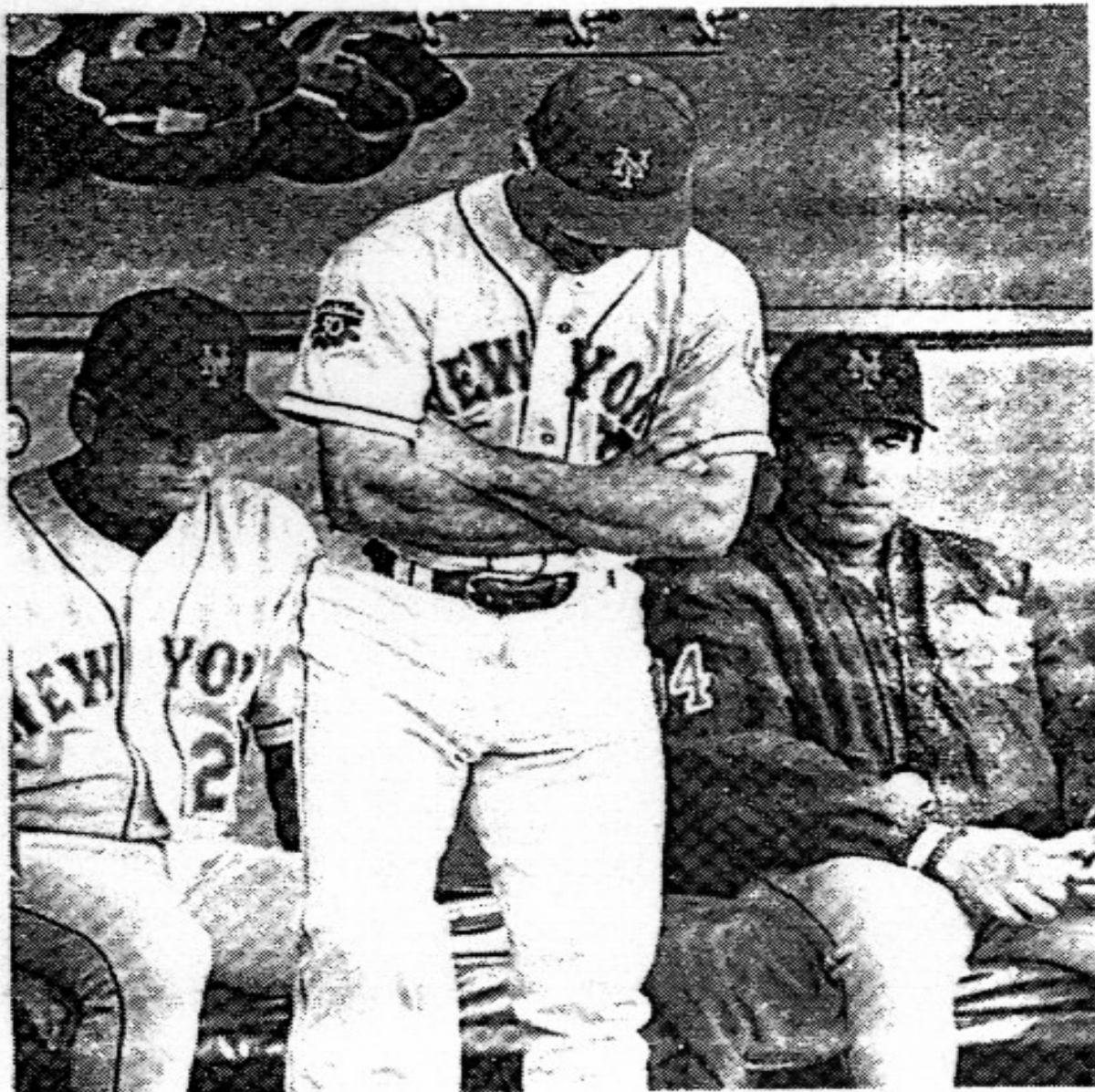
SAN DIEGO, April 1 — Even before the Mets began the 1997 season today, Manager Bobby Valentine would not endorse his bullpen. "It is what it is," he said.

What it is, on opening day, is embarrassing. Mets relievers inherited a 4-3 lead from starter Pete Harnisch in the bottom of the sixth inning, and before achieving three outs, the bullpen etched for itself a place in club history — the Padres scored 11 runs in the sixth, tying a single-inning record for Mets opponents. It was the most runs ever allowed by a National League team in one inning on opening day.

It is what it is: Padres 12, Mets 5. Only 161 more games to go, and there's no telling how many relievers the Mets will employ before the end of this season.

After watching Mets relievers blow many leads last season, General Manager Joe McIlvaine traded for relievers Toby Borland, Ricardo Jordan and Greg McMichael and intended to promote Derek Wallace into a more prominent role in the bullpen hierarchy.

But Wallace began losing feeling in his fingers, and following surgery for an aneurysm, he will miss most of the season. His injury seemed to create fissures in the fragile Mets bullpen, and three weeks into spring training, Valentine began to speak of his bullpen with strain in his voice. In the last five days, McIlvaine bought Barry





$z=50$

$z=10$

Quantum fluctuations  
just after Big Bang

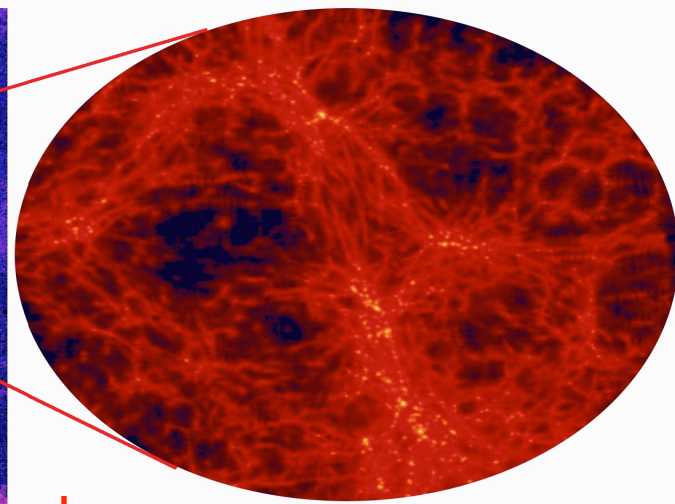
$z=3$

$z=1$

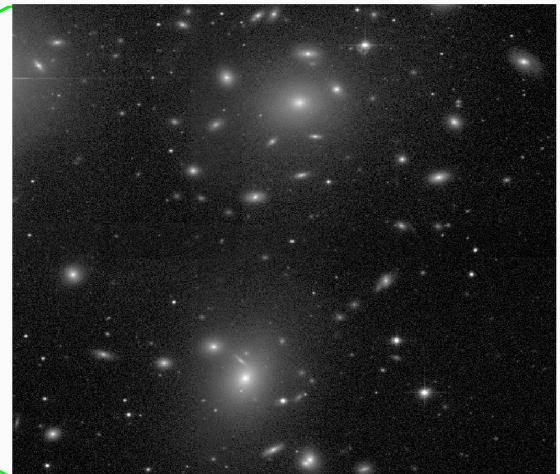
$z=0.5$

$z=0$

Today



Evolution of  
Structure in the  
Universe:  
Gravity is the  
engine

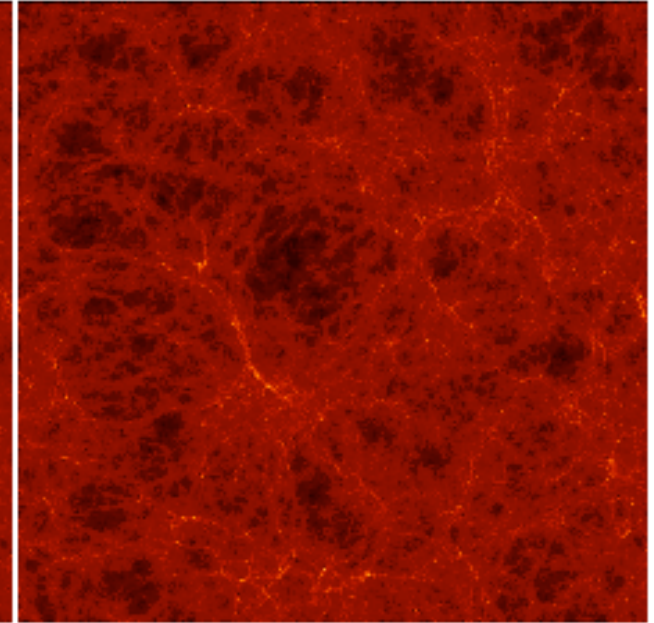
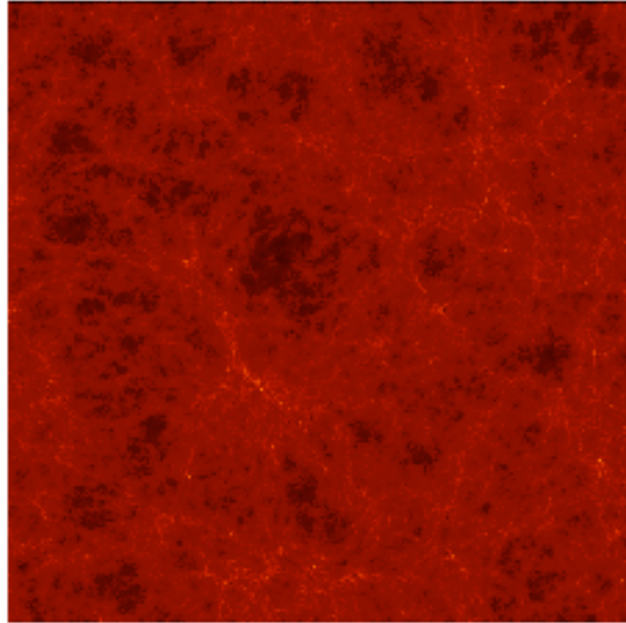




Early

$z=3$

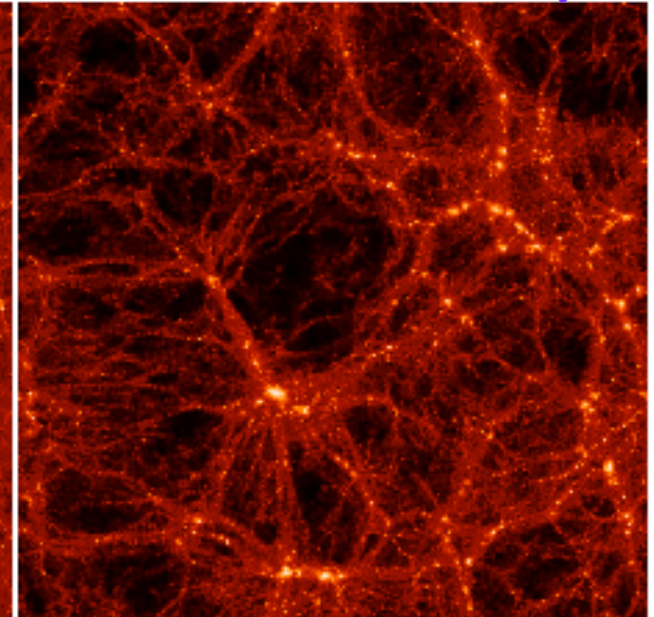
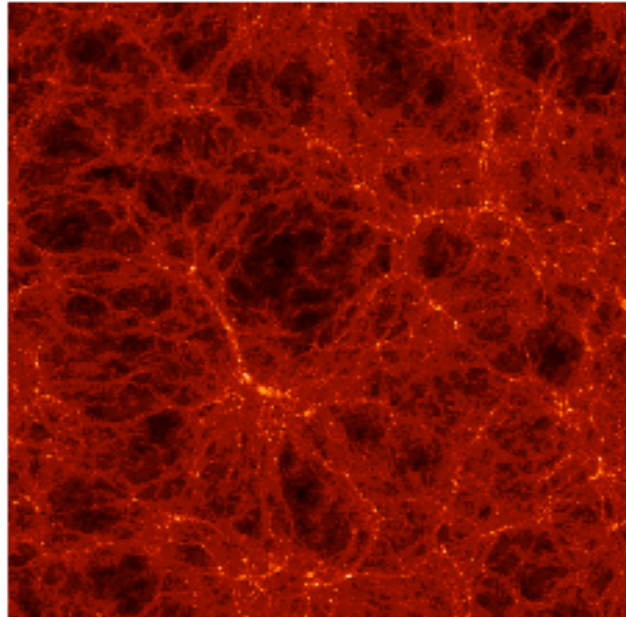
$z=2$



$z=1$

$z=0$

Today



# Evolution of Structure in a Simulated Universe filled with Dark Matter

‘The Cosmic Web’

Galaxies and  
Clusters form in  
sheets and filaments

Similar to the  
structures seen in  
galaxy surveys

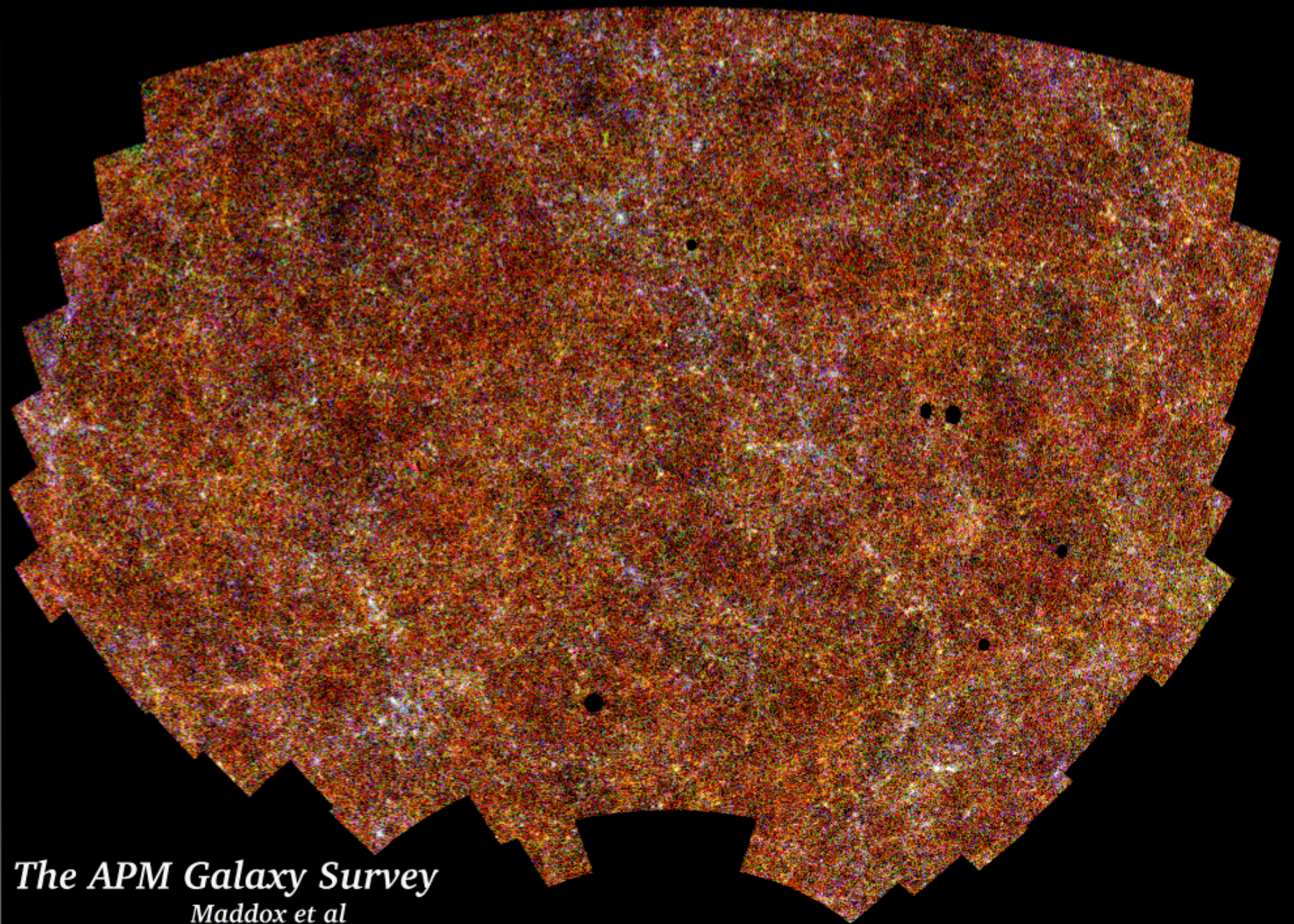
# Two Kinds of Galaxy Surveys

Photometric: imaging → 2D sky maps: positions, brightnesses  
(and colors if more than one band)



Spectroscopic: redshifts → distances (via Hubble's Law):  
3D maps





*The APM Galaxy Survey*  
*Maddox et al*

UK Schmidt Imaging Survey (photographic plates)



# Two Degree Field (2dF) Survey at the AAT

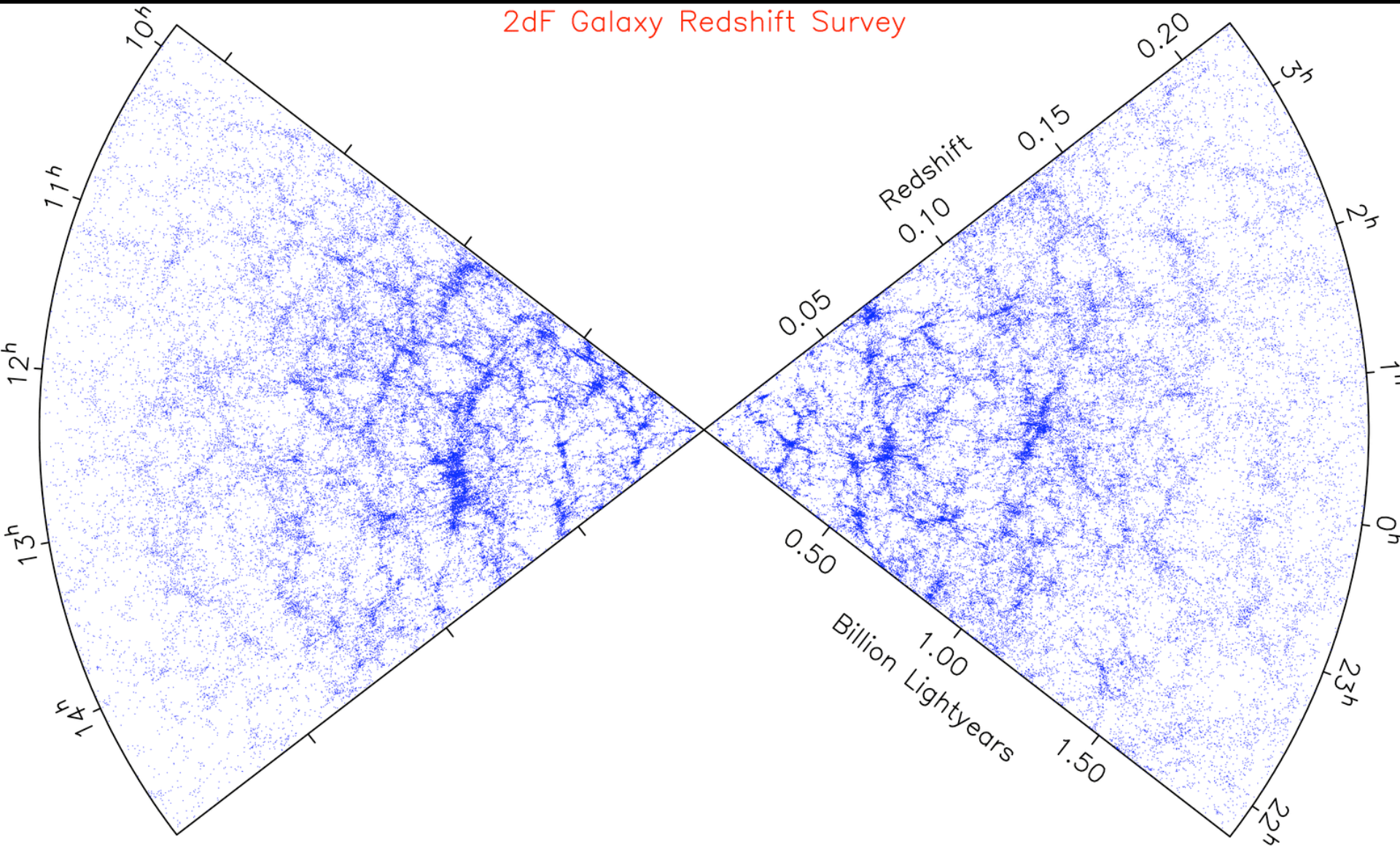
Galaxy  
Spectroscopic  
Targets  
selected  
from the  
APM  
Survey



400-fibre spectrograph with robotic positioner

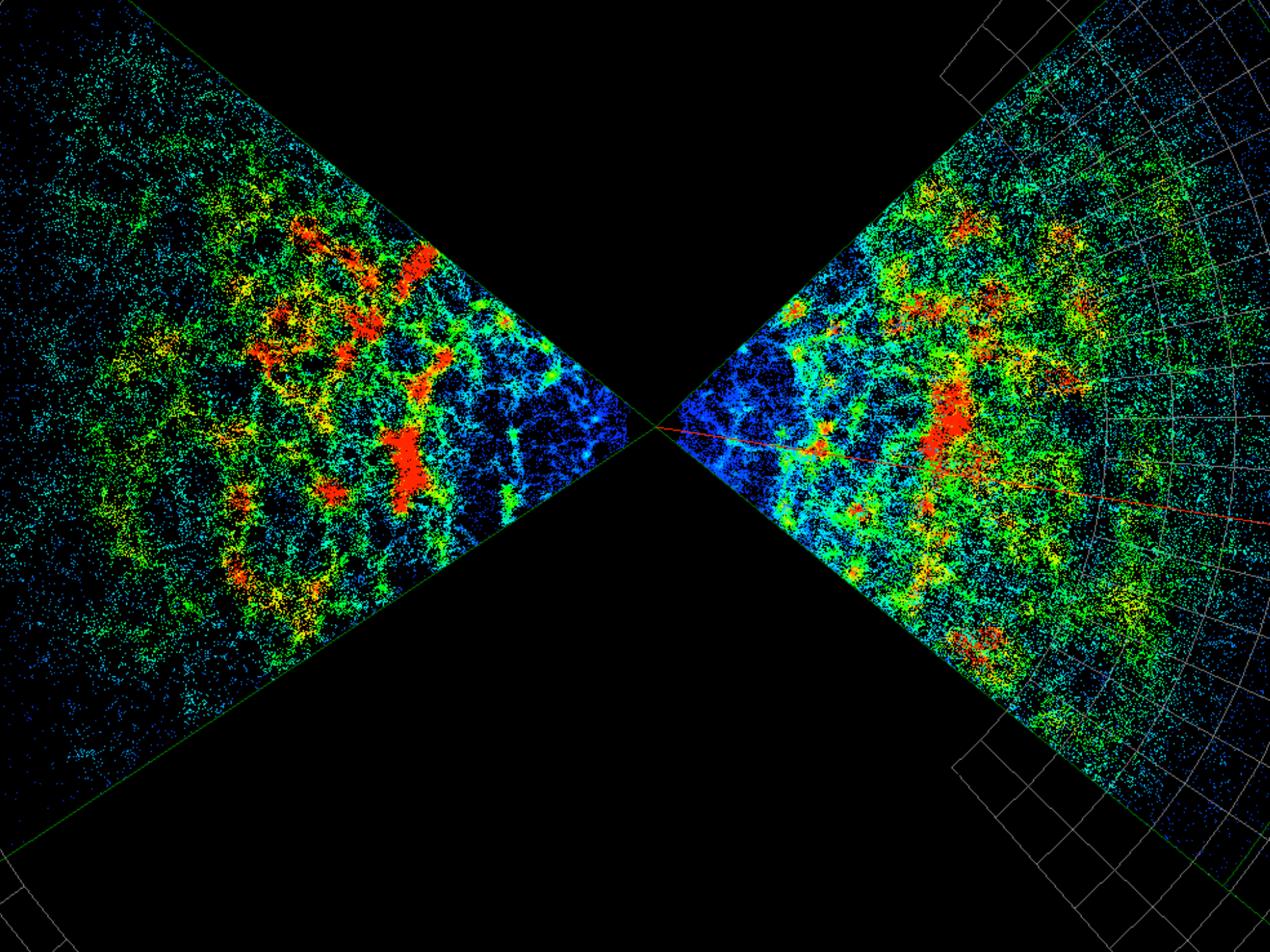


2dF Galaxy Redshift Survey



221283 galaxies

completed 2002





# SLOAN DIGITAL SKY SURVEY (2000-2008)



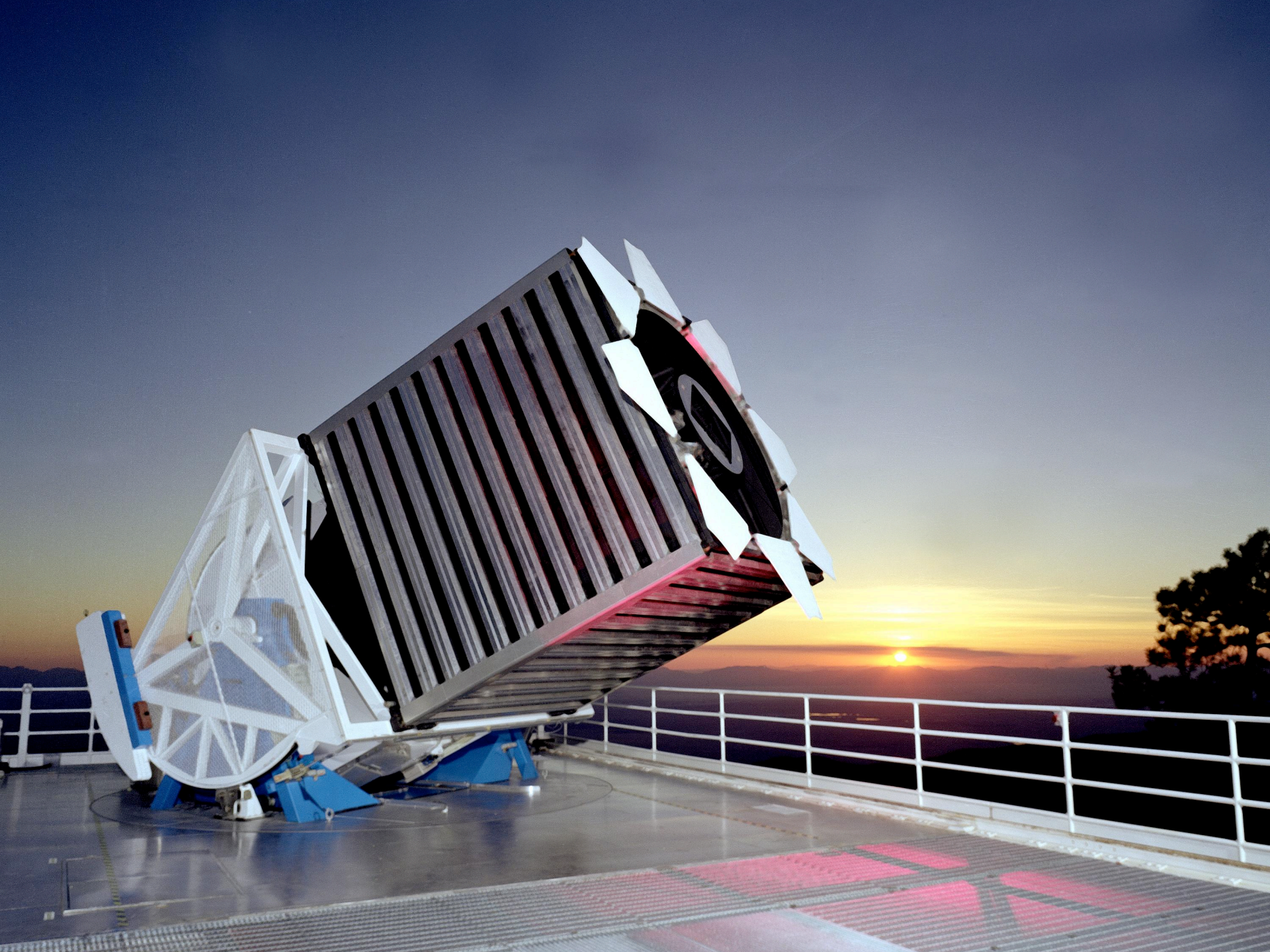
GOAL: MAP THE UNIVERSE IN 3 DIMENSIONS  
OVER A LARGE VOLUME

- Imaging Survey: ~100 million galaxies & stars
- Redshift Survey: ~1,000,000 galaxies and 100,000 quasars

covering  $\sim 1/4$  of the sky

<http://www.sdss.org>







# Apache Point Observatory Southern New Mexico



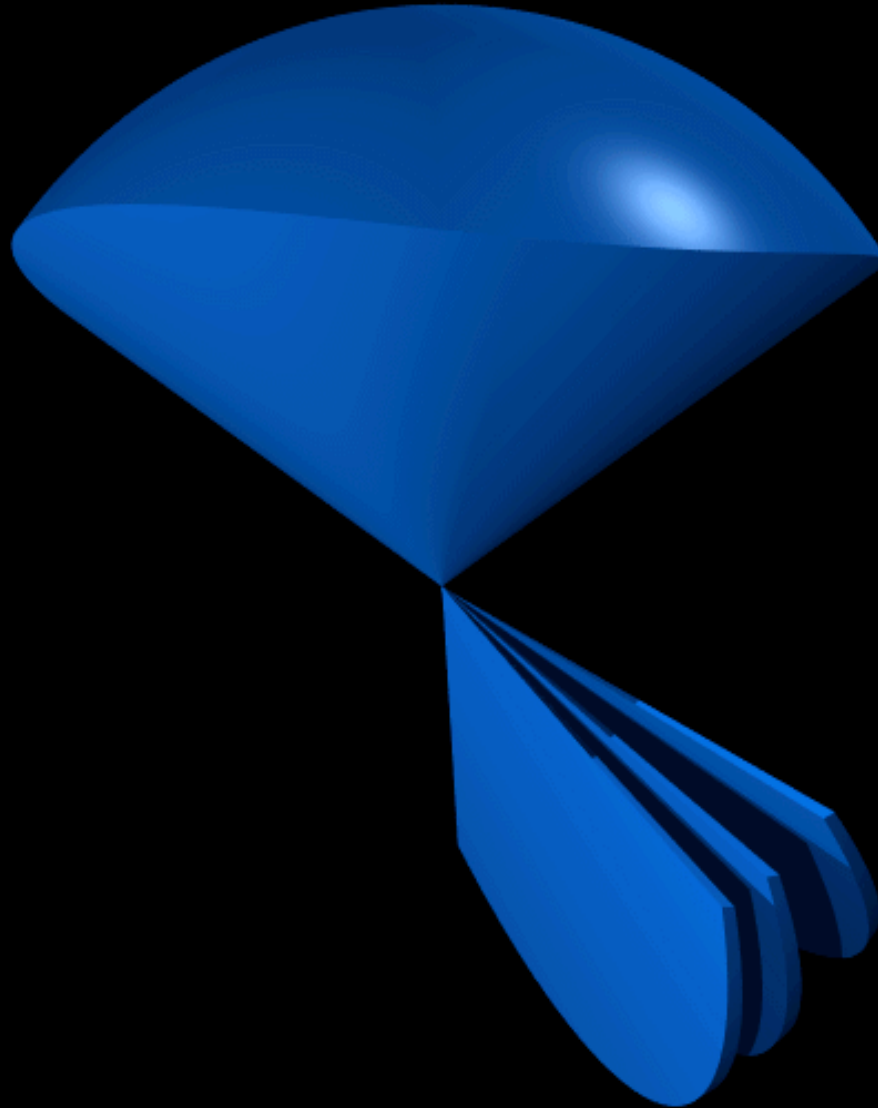


# Survey Geometry On the Sky:

Northern  
Survey:  
 $\sim 1/4$  the sky

Southern  
Survey:  
3 slices

(Look away  
from the  
Milky Way)





# SDSS Digital Camera

Top to bottom:

$g'$

$z'$

$u'$

$i'$

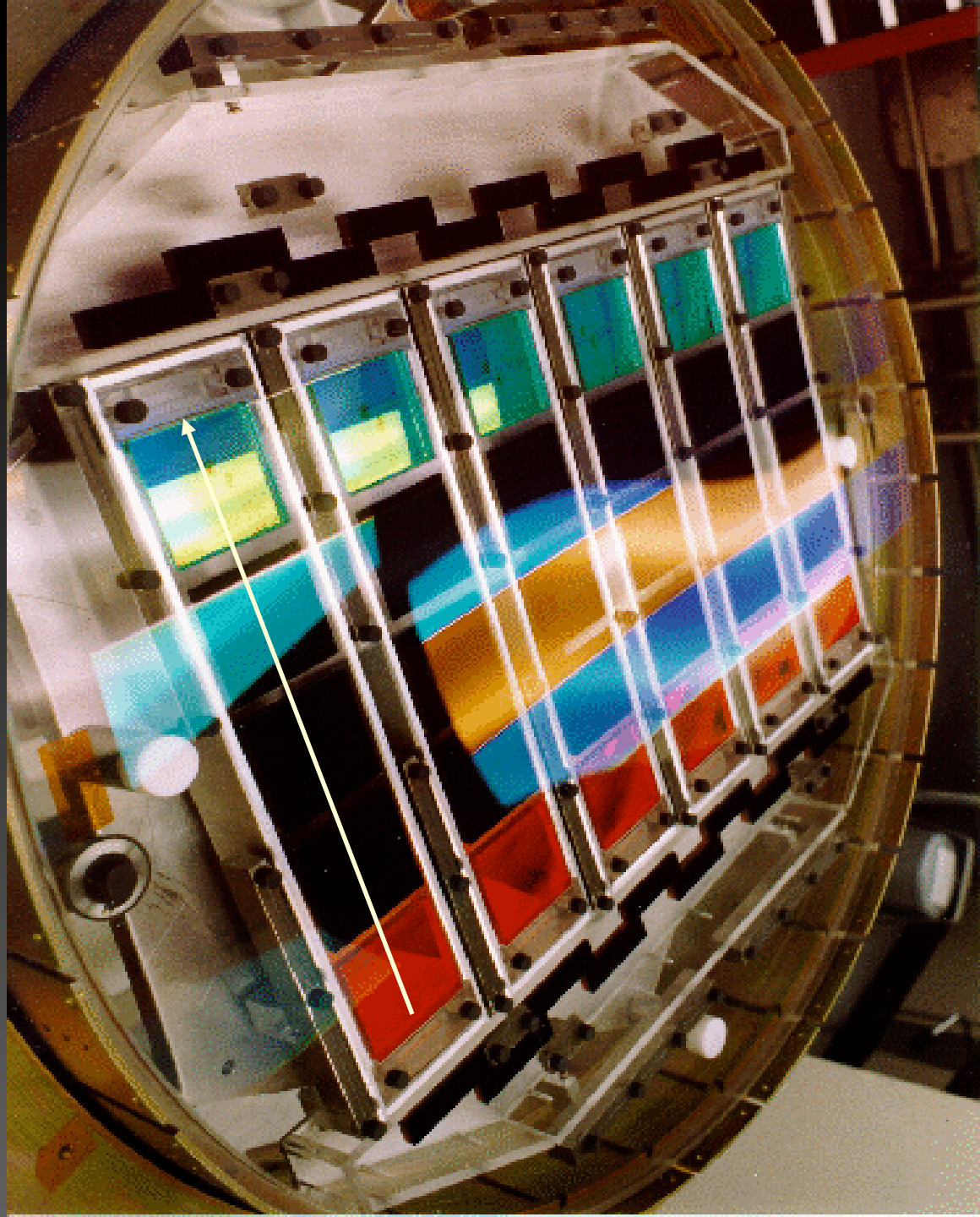
$r'$

filters

Drift Scan Mode

120 Megapixels

Cooled to  $-200$  degrees



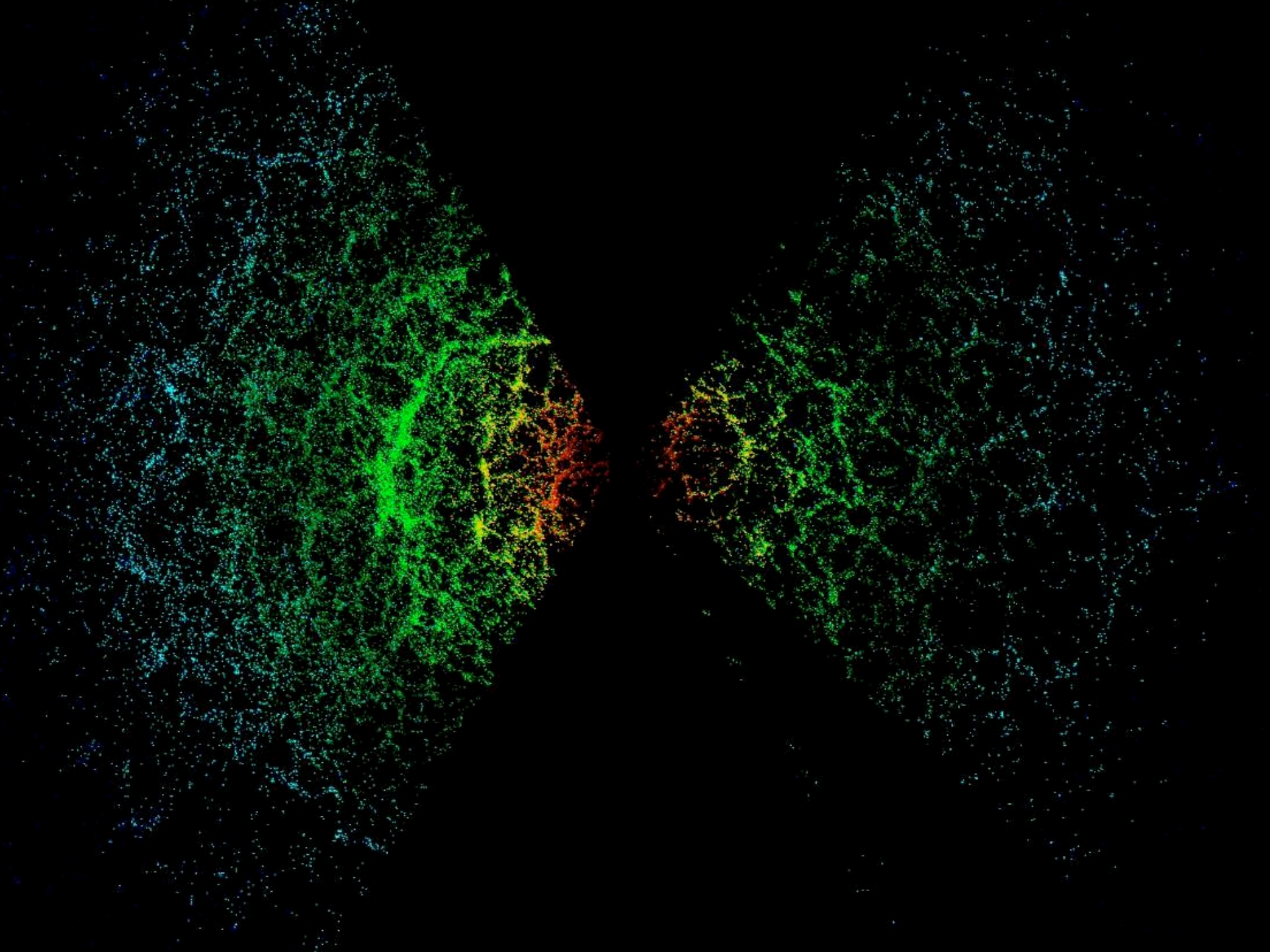
# Spectroscopic Plates for Redshift Survey



640 fibers per plate

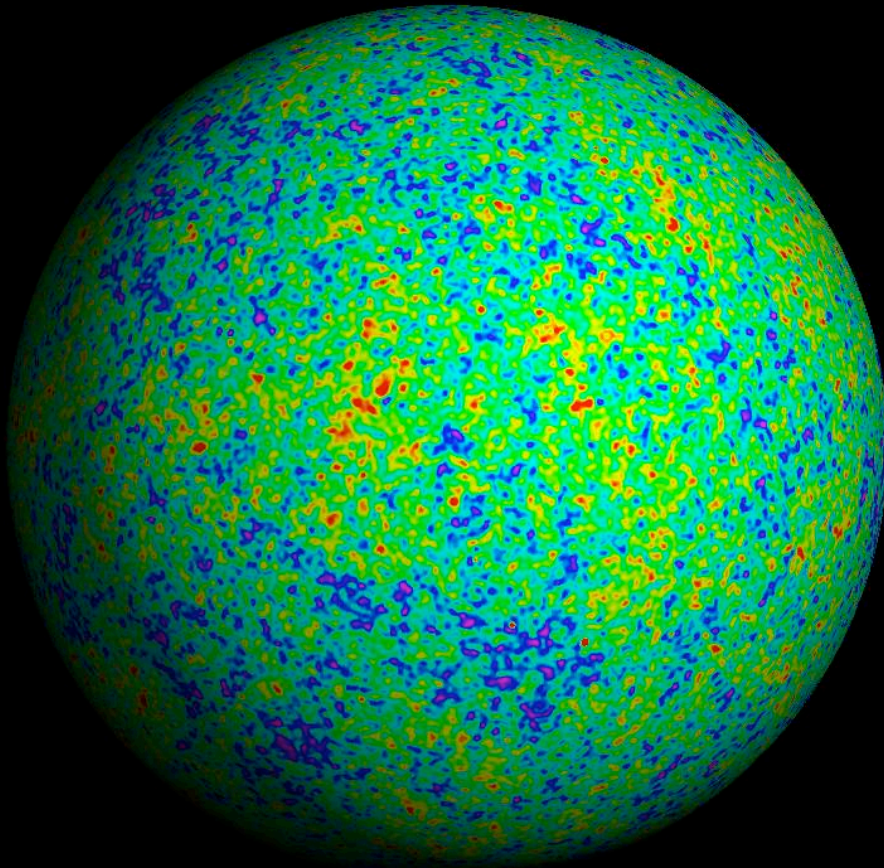








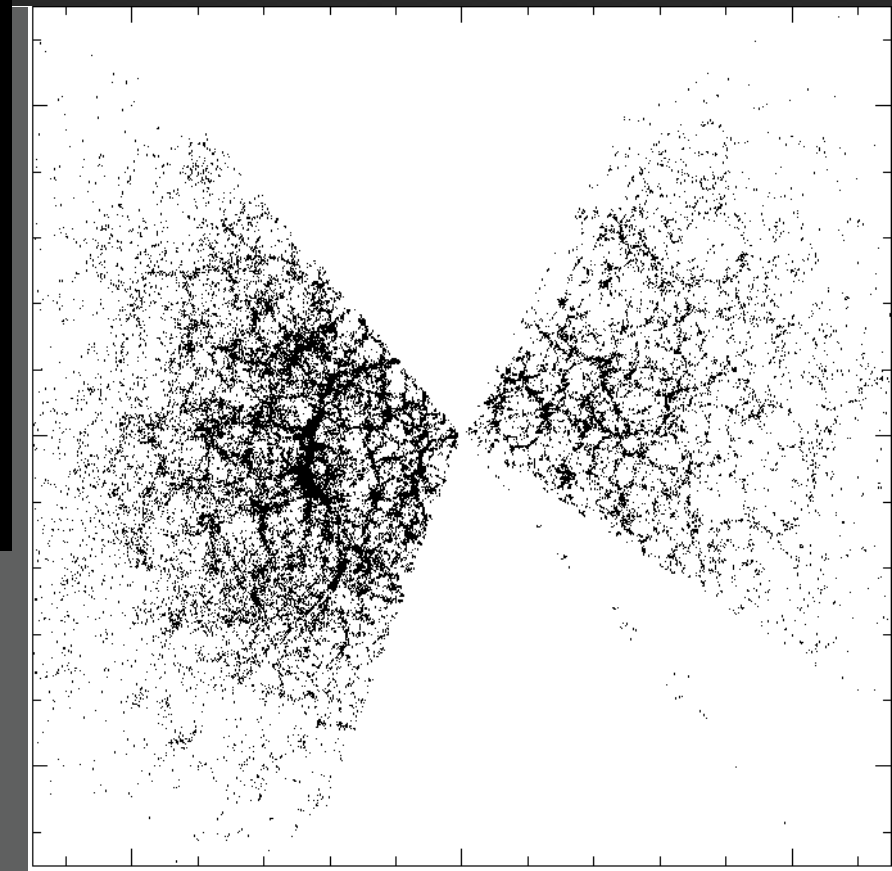
# Cosmic Microwave Background: Wilkinson Microwave Anisotropy Probe (WMAP)



Universe at 400,000 years

Combine these two to constrain Cosmology, e.g., the amount and properties of the Dark Matter

SDSS galaxies today



# Large-scale Galaxy Distribution: what have we learned?

Pattern of large-scale structure + Microwave background  
observations tell us:



# Large-scale Galaxy Distribution: what have we learned?

Pattern of large-scale structure + Microwave background observations tell us:

1. The Universe comprises:

- 5% Ordinary Matter (atoms, ...)
- 25% Dark Matter (exotic particles)
- 70% Dark Energy (even more exotic)

# Large-scale Galaxy Distribution: what have we learned?

Pattern of large-scale structure + Microwave background observations tell us:

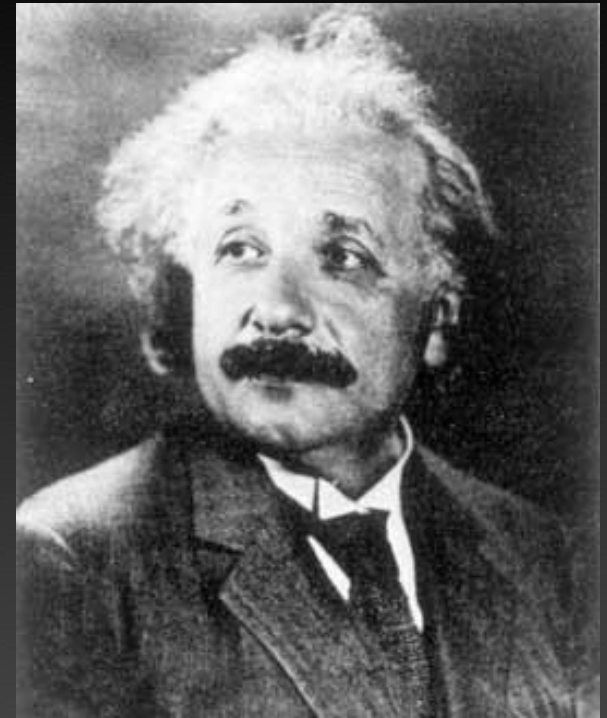
- [illegible]



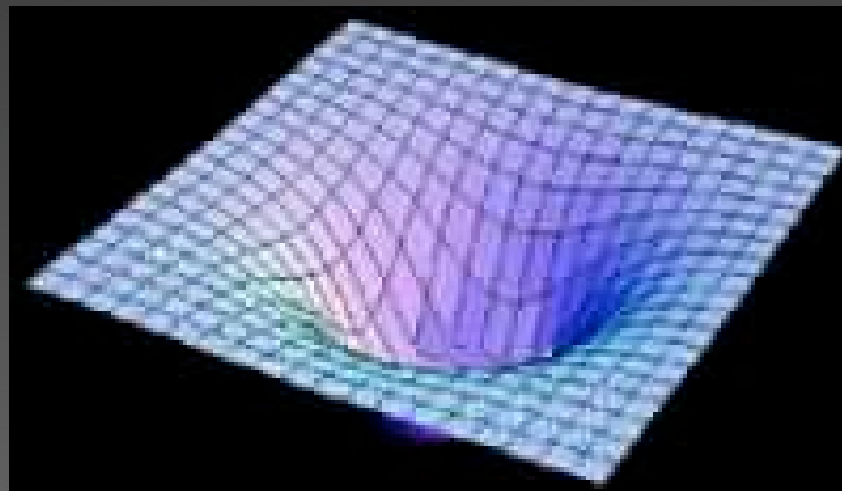
# Einstein's General Relativity

Matter and Energy curve  
Space-Time

Everything moves in this  
curved Space-time

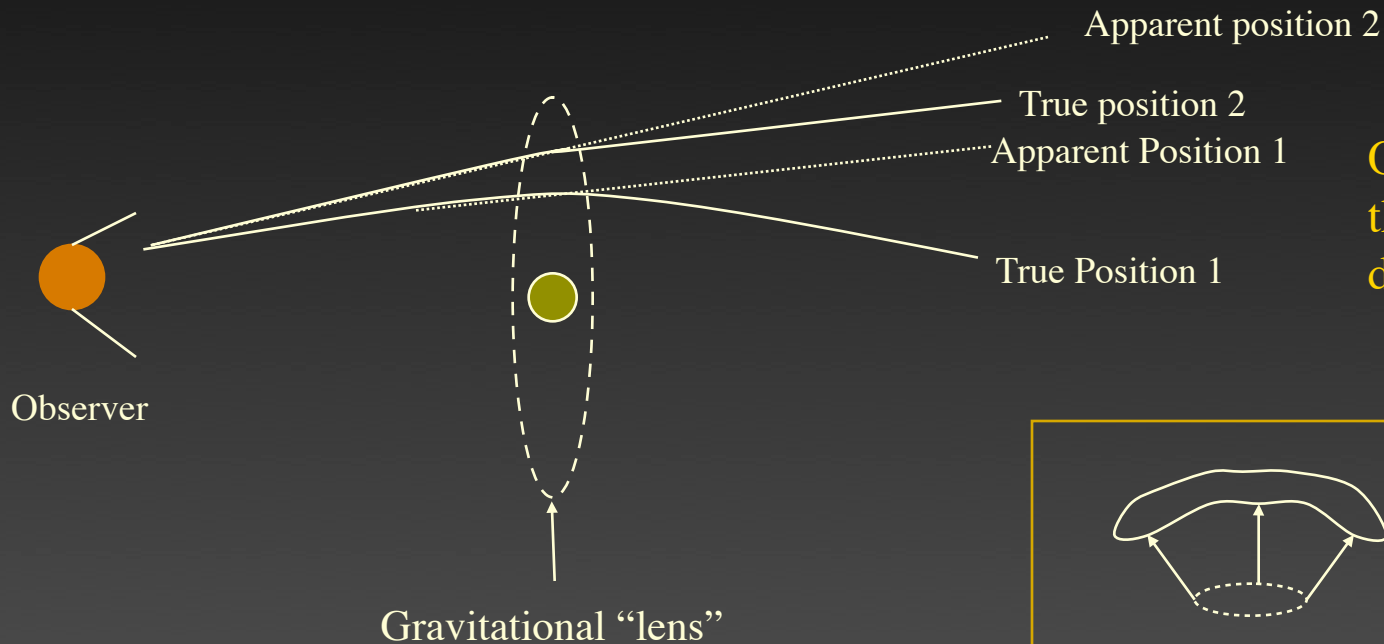


A massive star  
attracts nearby objects  
by distorting spacetime

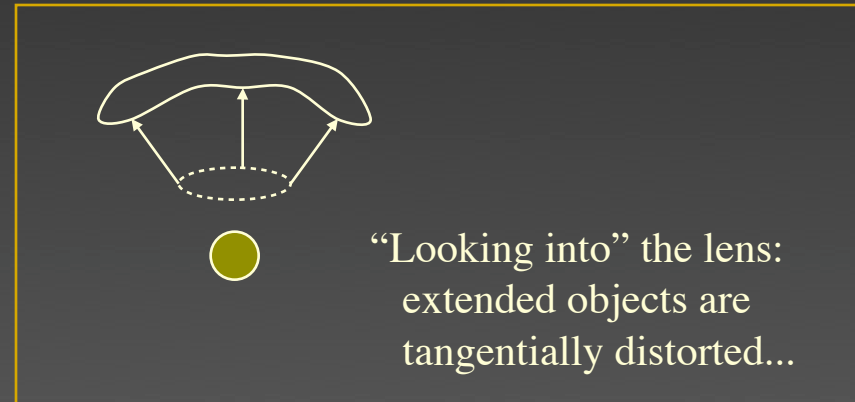


# Gravitational Lensing

magnification and distortion (shear)

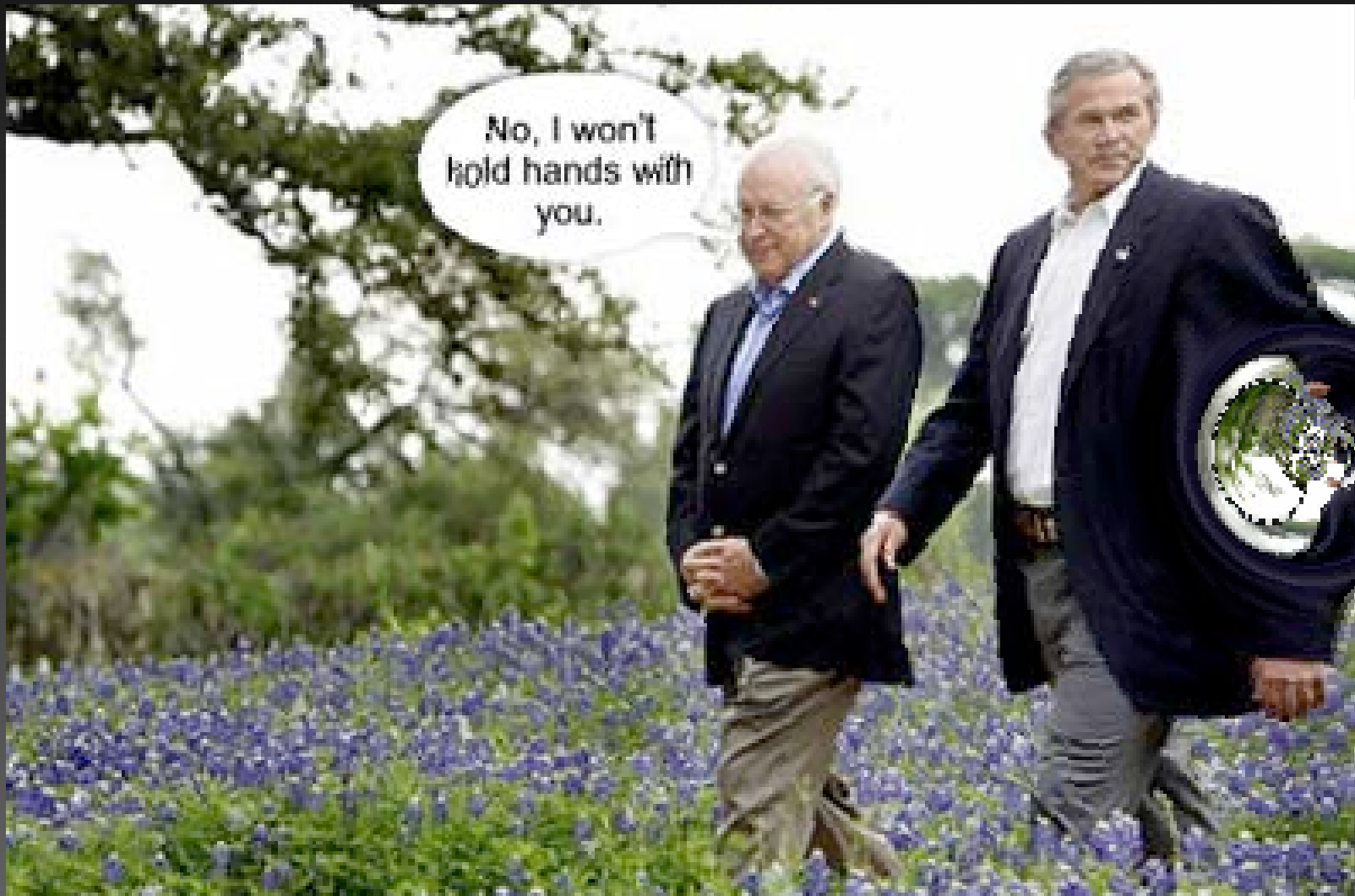


Objects farther from the line of sight are distorted less.

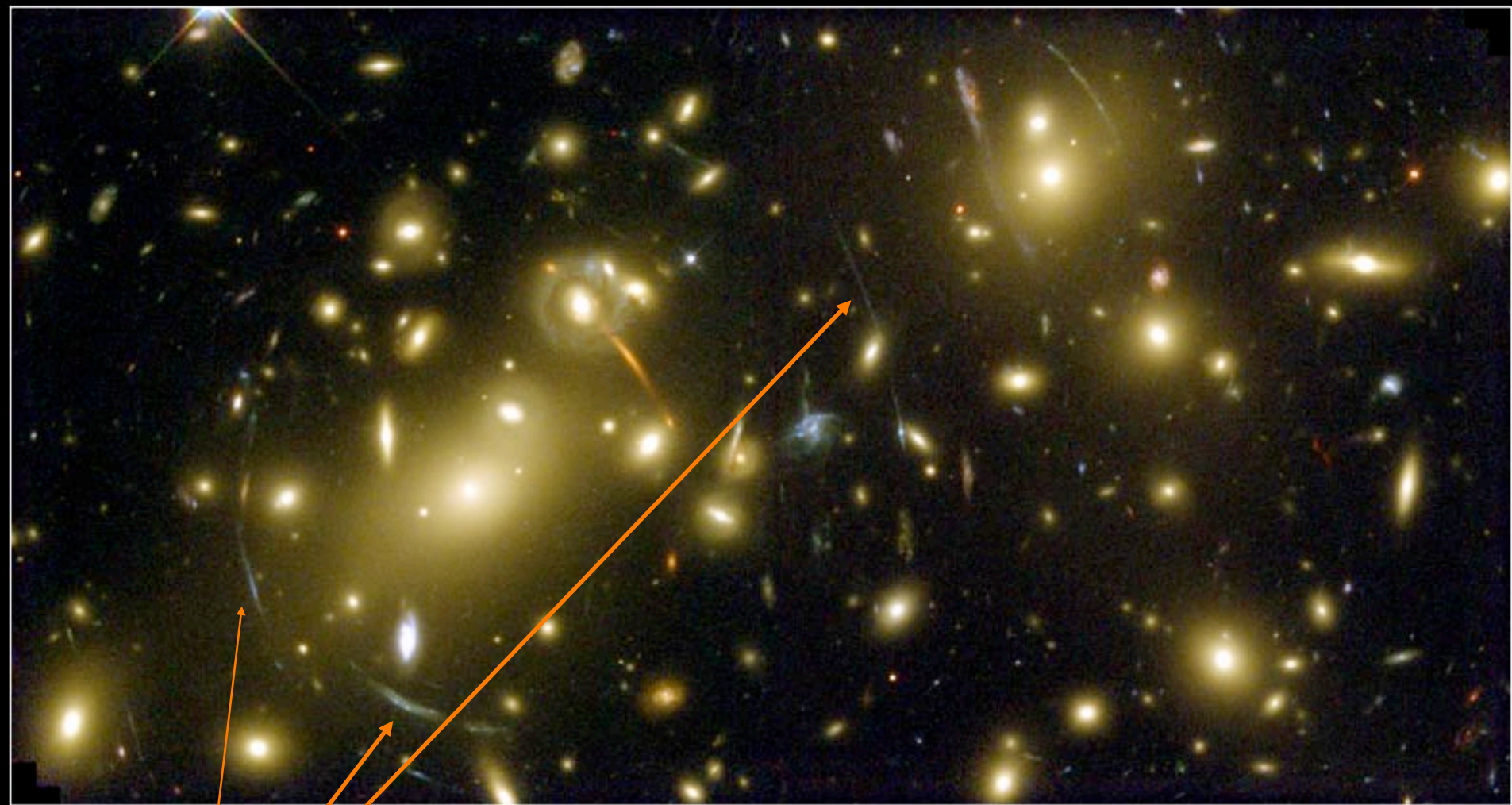




# Gravitational Lensing



# Cluster of Galaxies



**Galaxy Cluster Abell 2218**

**HST • WFPC2**

NASA, A. Fruchter and the ERO Team (STScI) • STScI-PRC00-08

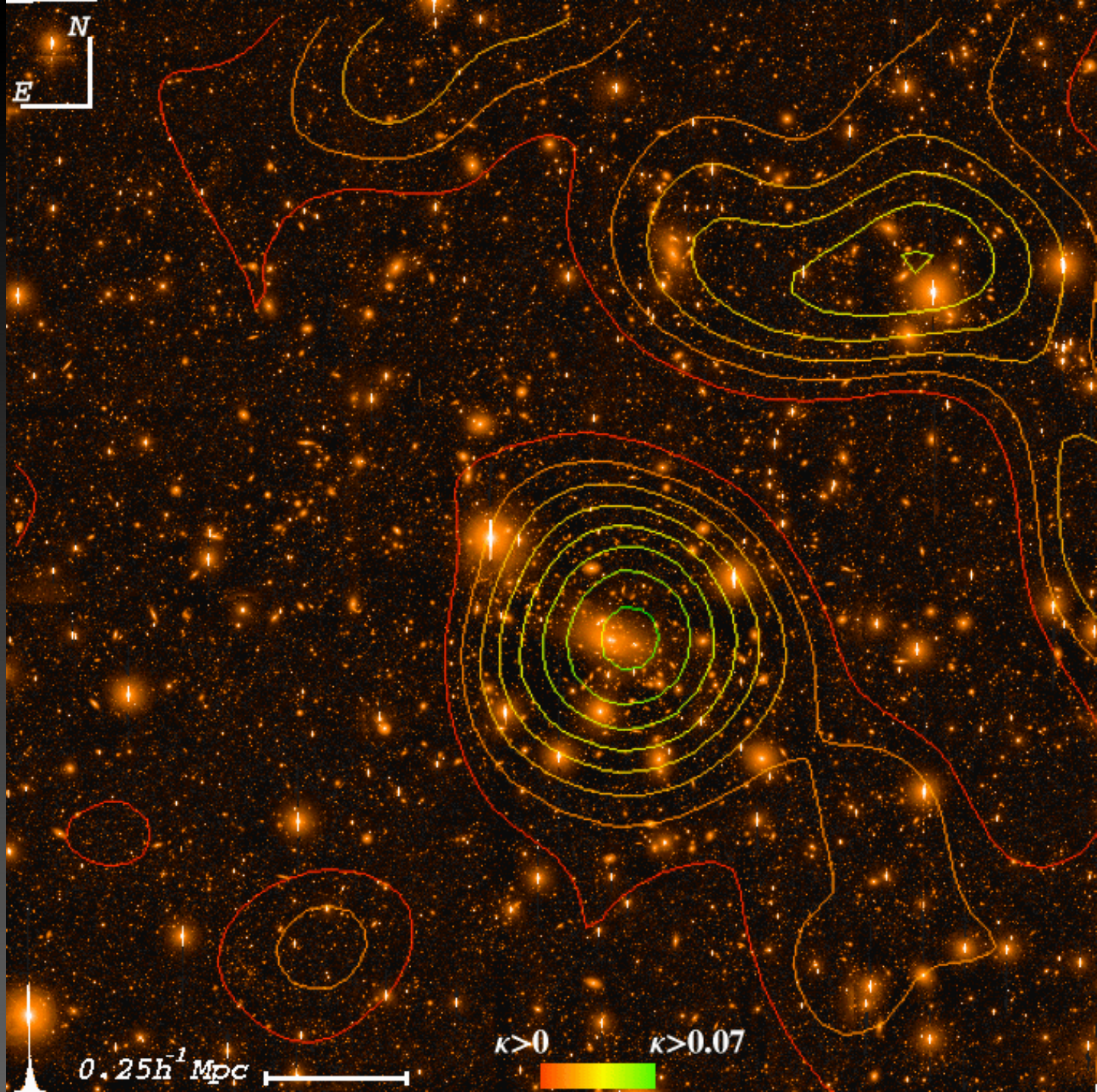
'giant arcs' are galaxies behind the cluster, gravitationally lensed by it



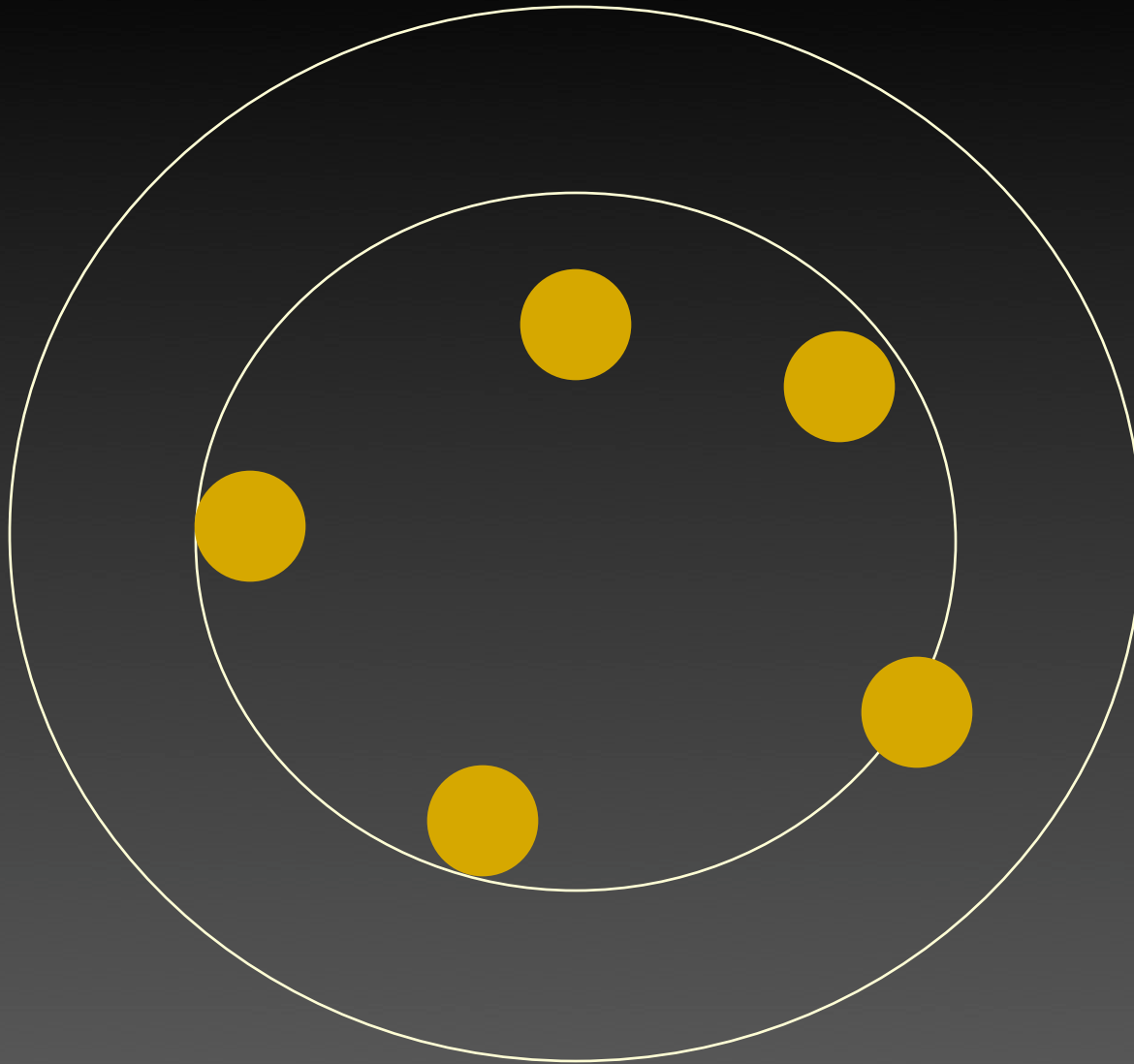
# Mapping the Mass in a Cluster of Galaxies via Weak Gravitational Lensing:

~90% of the  
Mass in the  
Universe is  
Dark  
(it doesn't  
shine)

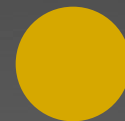
Dark Matter



# Faint Galaxies

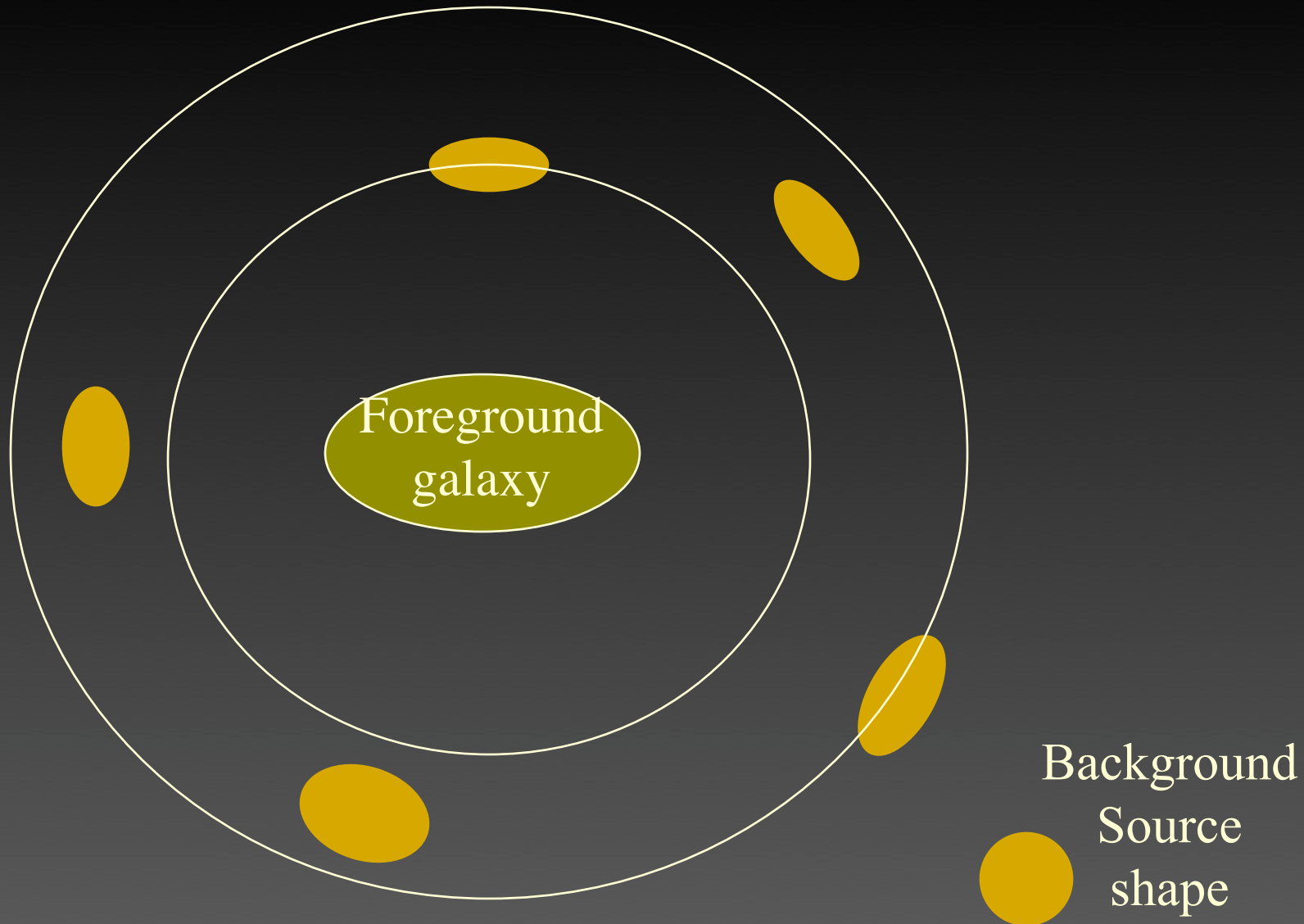


Background  
Source  
shape



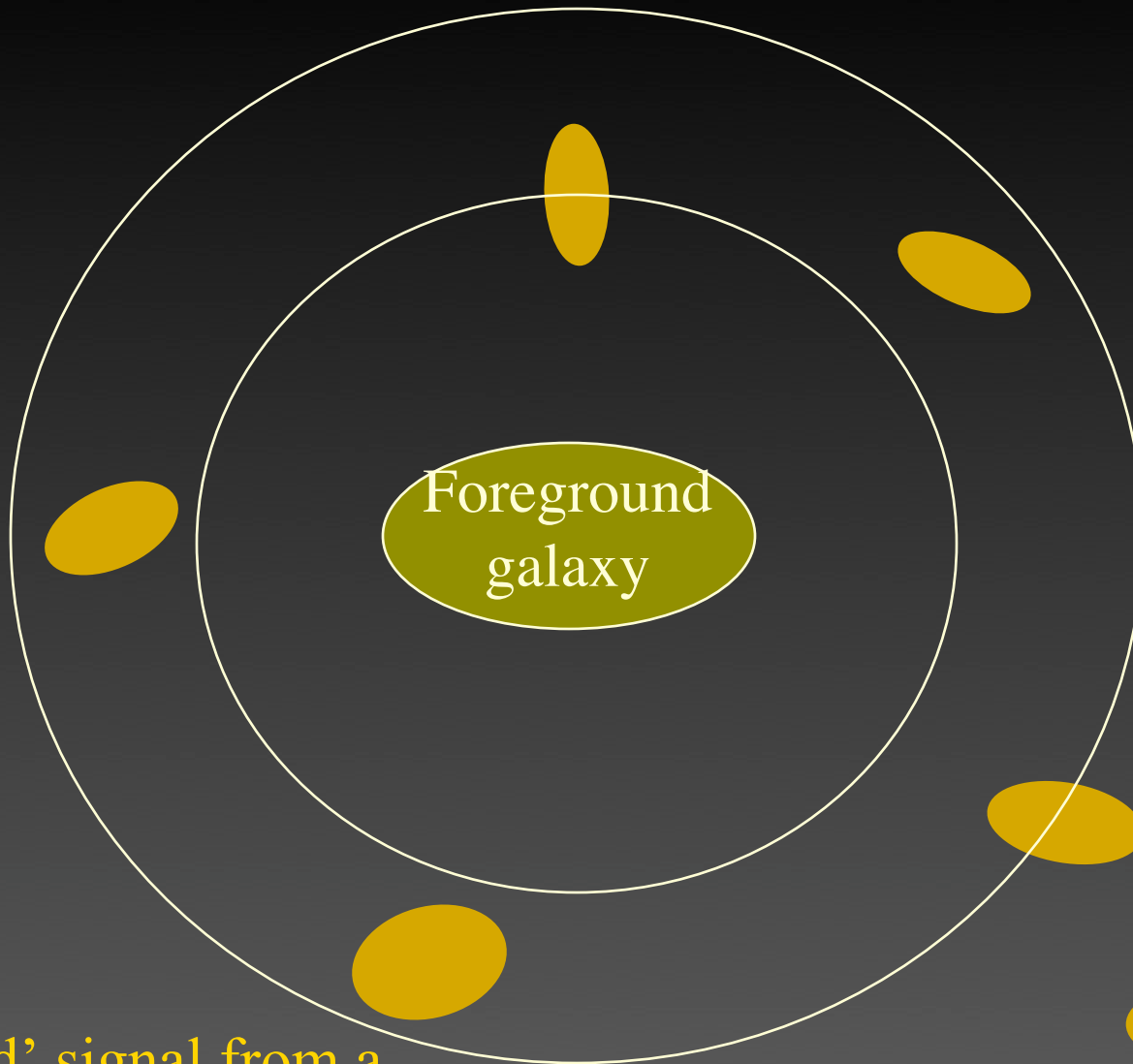


# Weak Lensing of Faint Galaxies: distortion of shapes



Note: the effect has been greatly exaggerated here

# Lensing of real (elliptically shaped) galaxies



Background  
Source  
shape

Must 'add' signal from a  
large number of foreground galaxies



December 14, 1999

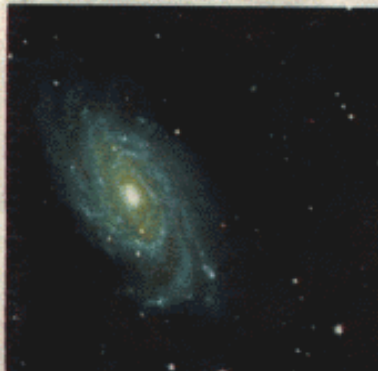
# Science Times

The New York Times

## Galaxies' Vastness Surprises Scientists

By JAMES GLANZ

Using a technique akin to overlaying thousands of faint X-ray images to create one sharp picture, astronomers have discovered that typical galaxies may be twice as large and contain twice as much mass as suggested by previous measurements. The new observations, which have emerged from a five-year census of the heavens called the Sloan Digital Sky Survey, indicate that an average galaxy extends invisibly for well over a million light-years into space and weighs the equivalent of at



A portrait of a woman far different from the cavewoman stereotype is emerging from these Stone Age Venuses: above is Venus of Willendorf in Austria; at right, the back and front views of Venus of Kostenki in Russia; far right, Venus of Lespugue, with prominent buttocks and a "grass" skirt, in southwest France.

By NATALIE ANGIER

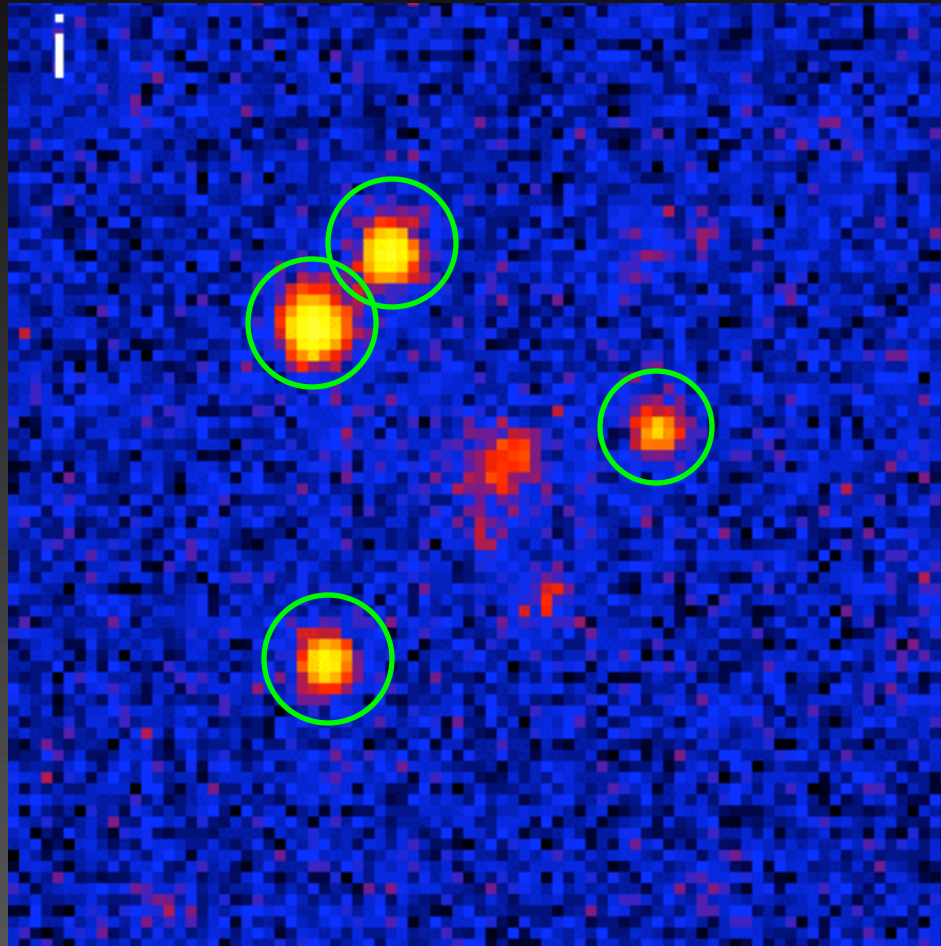
Ah, the poor Stone Age woman of our kitschy imagination. When she isn't getting bonked over the head with a club and

## Furs for But C The S Sta



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# Seeing Quadruple: Lensed Quasar



SDSS image: 4 images of the same quasar



Subaru image





# SDSS Data is made Public

- Data is being released in stages, semi-annually
- 4th Data Release a few days ago
- Access via the SkyServer website:

<http://cas.sdss.org>

excellent resource for education/outreach

- General information about the Survey:

<http://www.sdss.org>



# The Future

New Surveys with even more powerful telescopes

Virtual Observatory: Deskchair Astronomy

# SNAP SAT

Supernova / Acceleration Probe

*Studying the Dark Energy of the Universe*

## Joint Dark Energy Mission:

Proposed satellite to observe distant Supernovae and carry out deep Weak Lensing survey to probe the nature of the Dark Energy





# Large Synoptic Survey Telescope

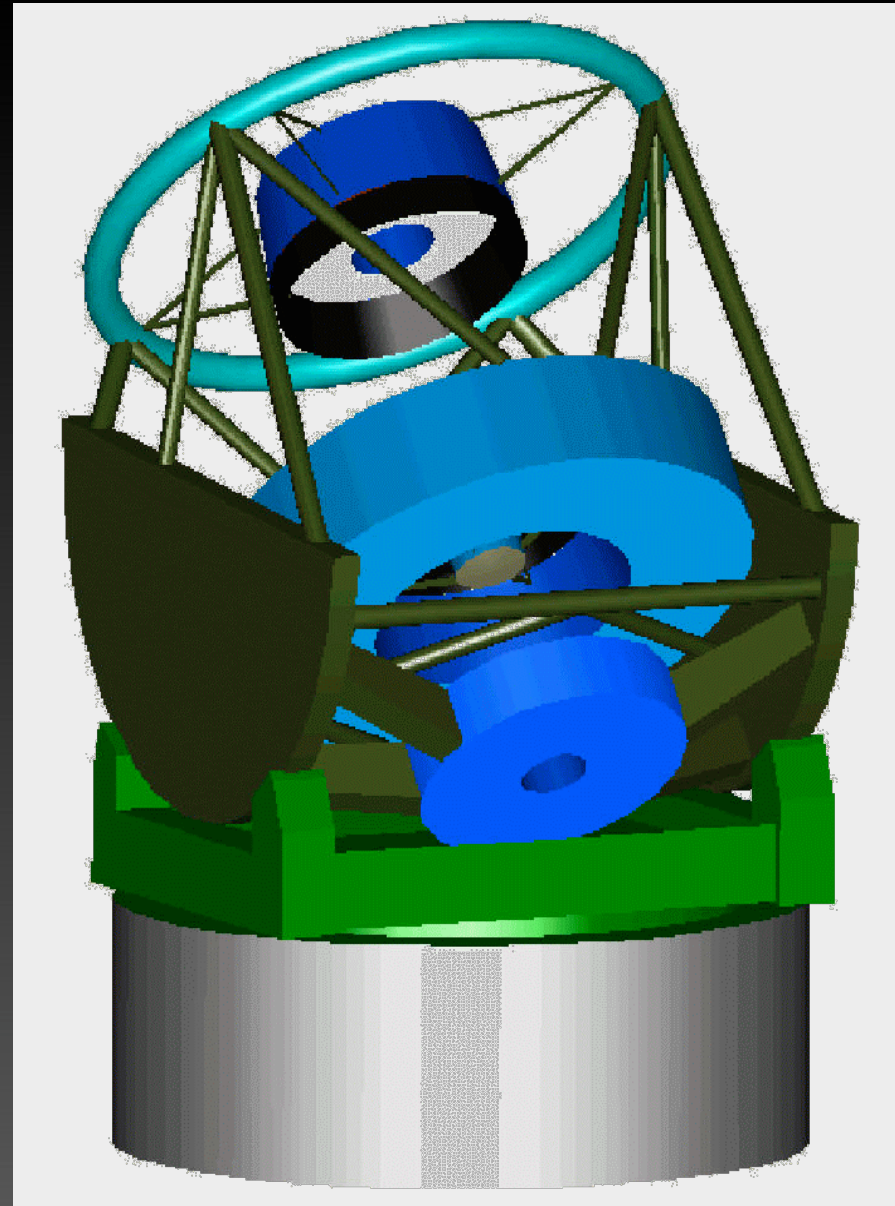
Proposed 8.5m ground-based telescope with 7 square degree field of view

5000 Gigabytes/night of data

Real-time analysis

“Celestial Cinematography”

Also: VISTA, DES,  
PANSTARRS,...



# Further Reading

Mercury, March/April 2003 (Vol. 32, No. 2):

Special Issue: Surveying the Universe

Articles on SDSS, 2MASS, 2dF, NVO

(Astronomical Society of the Pacific)



# 3d Flythrough Movie